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Spatially variable response of Himalayan glaciers to climate change affected by debris cover

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Controversy about the current state and future evolution of Himalayan glaciers has been stirred up by erroneous statements in the fourth report by the Intergovernmental Panel on Climate Change[1,2]. Variable retreat rates[3–6] and a paucity of glacial mass-balance data[7,8] make it difficult to develop a coherent picture of regional climate-change impacts in the region. Here, we report remotely-sensed frontal changes and surface velocities from glaciers in the greater Himalaya between 2000 and 2008 that provide evidence for strong spatial variations in glacier behaviour which are linked to topography and climate. More than 65% of the monsoon-influenced glaciers that we observed are retreating, but heavily debris-covered glaciers with stagnant low-gradient terminus regions typically have stable fronts. Debris-covered glaciers are common in the rugged central Himalaya, but they are almost absent in subdued landscapes on the Tibetan Plateau, where retreat rates are higher. In contrast, more than 50% of observed glaciers in the westerlies-influenced Karakoram region in the northwestern Himalaya are advancing or stable. Our study shows that there is no uniform response of Himalayan glaciers to climate change and highlights the importance of debris cover for understanding glacier retreat, an effect that has so far been neglected in predictions of future water availability[9,10] or global sea level[11].

Snow and glacial meltwaters make a important contribution to the drinking water, agriculture, and hydropower supply of densely populated regions in South and Central Asia[12,13]. Because global warming is expected to increase mountain–river discharge in the short term, but reduce it in the long term[9], detailed and reliable data on present-day climate change in mountainous Asia and its impact on the cryosphere are essential for predicting future water supplies[10]. However, the remoteness of this region hampers ground-based monitoring and results in very poor data coverage[7]. When mass-balance data are unavailable, scientists often refer to glacier retreats and advances as indicators of their response to climate change[7,14], but frontal changes are not unambiguous indicators. Supraglacial debris cover influences the terminus dynamics and can thereby modify a glacier's response to climate change. In the central Himalaya, recent studies found several debris-covered glaciers with stagnant, that is, non-flowing, glacier reaches that extend several kilometres upstream from their termini[15,16]. Although growing meltwater ponds and surface lowering indicate that such glaciers are currently shrinking, their fronts remain remarkably stable[17], as also been observed in other regions[18,19]. So far, however, the significance of debris cover and its impact on regional differences in the frontal dynamics of Himalayan glaciers has not been established at the mountain-belt scale.

Here, we assess regional differences in the terminus dynamics of glaciers in the greater Himalaya from remotely-measured frontal changes and mean annual glacier-surface velocities between 2000 and 2008. Our aim is to determine if glaciers in this region at present behave in a similar fashion or if distinct spatial patterns can be detected and related to climatic and/or other factors. Specifically, we want to test if regional disparities in the distribution of debris-covered glaciers provide simple explanations for spatial variations in glacier terminus dynamics. Therefore, we also mapped debris-covered areas from satellite images.

We analysed 286 mountain glaciers with 2–70 km lengths from 12 heavily ice-covered areas between the Hindu Kush (∼72° E, 36.5° N) and Bhutan (∼90° E, 28° N), and distinguished six geographic regions that differ in climate and topography (Fig. 1a). From the Hindu Kush and Karakoram and across the western Himalaya to the central Himalaya, these regions are characterized by the decreasing influence of the mid-latitude westerlies and the increasing influence of the Indian monsoon[13]. Because there are steep N–S gradients in surface elevation, topographic relief, and precipitation in the central Himalaya[13], we further distinguish glaciers located south and north of the main Himalayan crest. The West Kunlun Shan at the northwestern edge of the Tibetan Plateau is the most continental setting we studied, marginally influenced by the East Asian Monsoon (Fig. 1a).

From satellite images we determined frontal changes for 255 of the 286 glaciers. Between 2000 and 2008, retreating, stable, and advancing glacier fronts are observed in each study region, with rates between -80 and $+40\,\mathrm{m\,yr^{-1}}$ (Fig. 1b), comparable to reported longer-term average values[3,5]. In the Karakoram however, 58% of the studied glaciers were stable or slowly advancing with a mean rate of about $+8\pm12\,\mathrm{m\,yr^{-1}}$ (1σ). This contrasts with all other regions, where ≥65% of the analysed glaciers were retreating. We observe the highest concentration of retreating glaciers (79–86%) and also some of the highest rates (∼$60\,\mathrm{m\,yr^{-1}}$) in the western Himalaya, northern central Himalaya, and the West Kunlun Shan, where the proportion of debris-covered glaciers is relatively low (Fig. 1a). In the southern central Himalaya and Hindu Kush, where debris cover is common and high, 65% and 73% of the studied glaciers, respectively, have been retreating, but at slower rates.

To assess the impact of debris cover on glacier terminus dynamics, we measured surface velocities along the central flowline of each glacier and determined the fraction of stagnant ice as a function of distance upstream from the terminus (Supplementary Figs S1,S2). Uncertainties in the remote-sensing derived glacier surface velocities (u) are ∼$2.5\,\mathrm{m\,yr^{-1}}$ (Supplementary Table S4), which we thus take as a lower bound to discriminate moving ice from quasi-stagnant ice (that is, $u<2.5\,\mathrm{m\,yr^{-1}}$; hereafter termed 'stagnant' for simplicity). In general, mean annual frontal changes converge towards zero when an increasing part of the glacier is stagnant (Fig. 2). Where >10% of a glacier (by length) is stagnant, all observed frontal changes are statistically indistinguishable from

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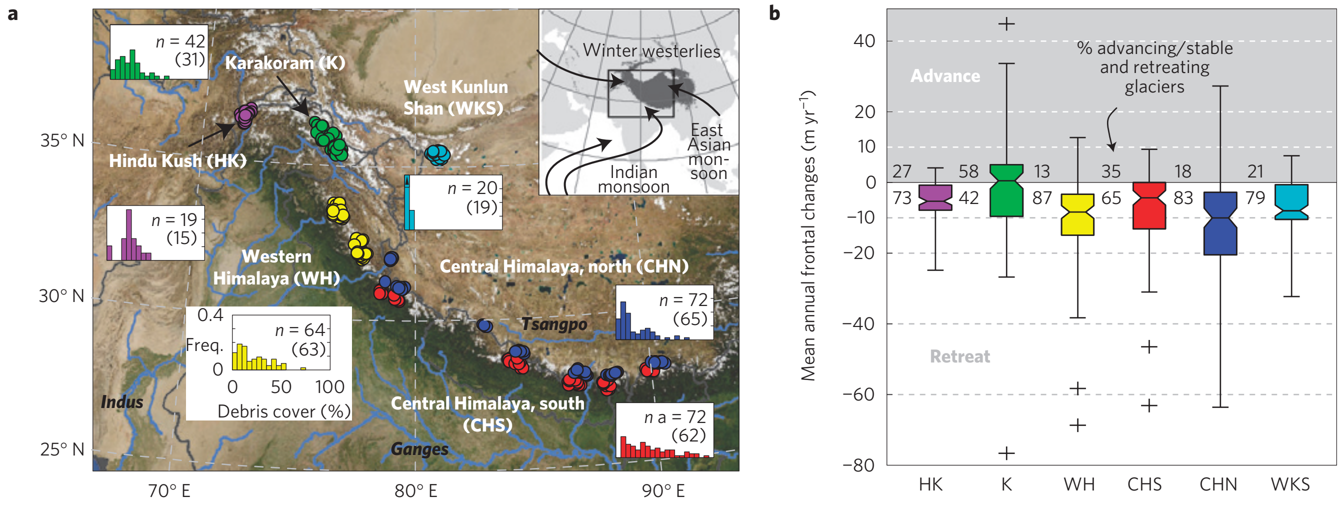

Figure 1 | Regional distribution of debris-covered and stagnating glaciers. a, Location of glaciers (circles) grouped by region. Histograms give relative frequencies (y-axis, 0–40%) of debris cover (x-axis, 0–100% in 5% bins). Number of studied glaciers is given in upper-right corner, measured frontal changes in parentheses. Globe depicts location of subset and atmospheric transport directions. **b**, Regional distribution of mean annual frontal changes. Boxes give lower and upper quartiles and median (notches indicate 95%-confidence intervals). Whiskers extend 2.5 times the interquartile data range, crosses lie outside this range. Numbers left of boxes indicate percentage of advancing/stable (top) and retreating (bottom) glaciers.

zero, that is, glacier fronts are stable. Such glaciers have on average >40% debris-covered areas (Fig. 2).

The regional distribution of stagnant glaciers varies considerably in the greater Himalaya. Stagnant glaciers with stable glacier fronts are most common in the Hindu Kush (16%) and in the southern (28%) and northern (10%) central Himalaya, rare in the western Himalaya (1.5%), and absent in the Karakoram and West Kunlun Shan. These regional differences in the distribution of stagnant debris-covered glaciers can mostly be explained by topographic differences (Fig. 3). High and deeply incised mountain ranges (southern central Himalaya, Hindu Kush, Karakoram) contrast with low-relief landscapes on the Tibetan Plateau (West Kunlun Shan and parts of the northern central Himalaya). Because hillslope-erosion rates usually increase with hillslope angle[20], the flux of rocky debris to the glacier surfaces and therefore the formation of debris-covered glaciers are linked to steep (>25°) accumulation areas (Fig. 3a). However, the development of stagnant ice implies low gravitational driving stresses, which are counteracted by steep glacier beds. Therefore, stagnant ice is confined to terminus regions of debris-covered glaciers with shallow gradients of <8° (Fig. 3b).

According to simple modelling, the length change and timescale of a glacier's response to climate change are inversely proportional to its surface slope and also depend on local climate and glacier size[14]. However, these factors do not adequately explain the observed different retreat rates between debris-free and debris-covered glaciers (Supplementary Figs S4,S5). In summary, widespread debris cover on many Himalayan glaciers reduces their retreat rates, which are therefore unsuitable as indicators of recent climate change. Nevertheless, glaciers with extensive stagnant reaches indicate negative mass balances[15–17], and have the potential to build up hazardous moraine-dammed lakes[15,19].

Accumulation areas in the Karakoram are relatively steep (mean hillslope angles 25°–35°), and debris cover and shallow (<8°) termini are frequent, but stagnant glaciers are almost absent (Fig. 3). Therefore, the >50% stable or advancing glaciers (Fig. 2b) are unrelated to stagnant terminus regions, and most probably a consequence of different mass-balance regimes associated with their climatic setting. Long-term glacier and climate records from high elevations in the Karakoram are virtually absent, but historical changes in westerly-derived winter precipitation could account

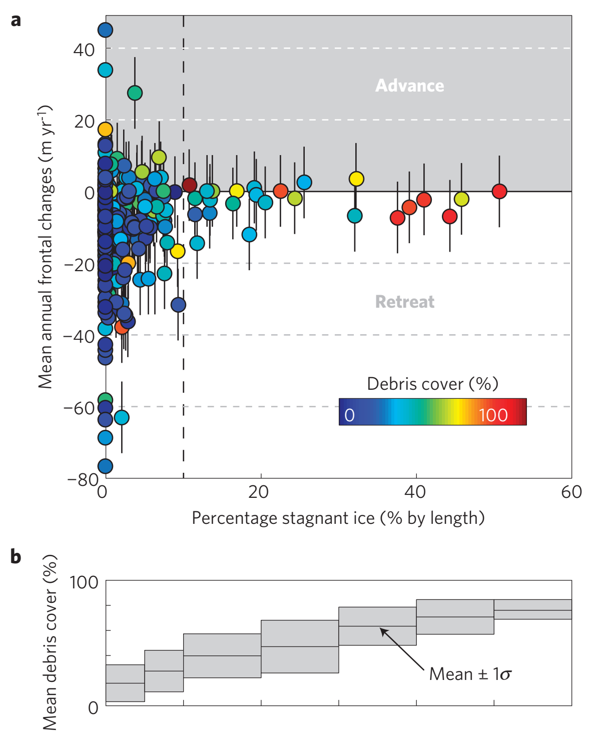

Figure 2 | Glacier advance and retreat rates. a, Scatter plot of percentage stagnant ice with surface velocity <2.5 m yr^{-1} versus mean annual frontal changes. Error bars reflect mapping uncertainties, conservatively estimated at ±10 m yr^{-1}. Marker-symbol colours denote the areal fraction of debris cover. Glaciers with >10% stagnant ice (vertical-dashed line) have high debris cover (>40% on average) and stable glacier fronts. **b**, Mean debris cover versus percentages of stagnant ice (percentage by length) in 5 and 10% bins.

for a positive mass-balance perturbation. First, the westerly jet stream over central Asia, which is the principal engine of moisture transport during winter, has strengthened and shifted to lower elevations in recent decades[21]. Second, tree-rings from the Karakoram record an increase in 20th-century winter precipitation[22].

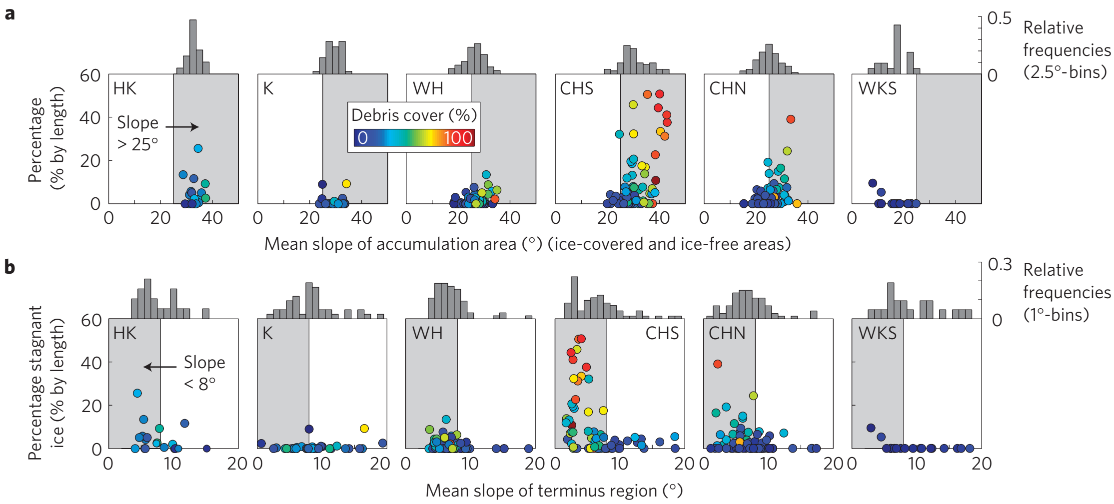

Figure 3 | Topographic influence on debris cover and glacier stagnation. a, Mean slope of accumulation areas (catchment and glacier areas above snowline) versus percentage of stagnant ice (percentage by length). Mean slope angles >25° promote rock falls and snow avalanches. **b**, Mean slope of terminus region (lowermost 1–2 km of the glaciers, depending on glacier size) versus percentage of stagnant ice (percentage by length). Mean surface slopes in the terminus region <8° promote the development of stagnant ice. Histograms above each plot show relative frequencies of mean slopes. Colour coding depicts areal fraction of debris cover.

Table 1 | Regional distribution of debris-covered glaciers.

Geographic region	Hindu Kush	Karakoram	Western Himalaya	Central Himalaya (South)	Central Himalaya (North)	West Kunlun Shan
Number of studied glaciers	19	42	64	72	72	20
Ice-covered areas (km^2)	428	3,123	1,150	973	1,212	1,321
Debris-covered areas (%)	22	18	21	36	19	2
Glaciers (>20% debris cover)	74	50	45	67	33	0
Ice volume (glaciers >20% debris cover)	88	74	77	89	68	0

See Fig. 1 for geographic regions.

Third, summer temperatures in the Hindu Kush, Karakoram, and western Himalaya have slightly decreased in the second half of the last century, which may be related to higher precipitation and cloudiness[23]. Although all these factors could affect the glacial mass balance in regions influenced by westerlies (that is, the Karakoram and Hindu Kush), the observed striking differences in terminus dynamics between the Karakoram and Hindu Kush point to additional factors that are unique to the Karakoram. To assess the reason for this anomalous glacier behaviour, long-term mass balance monitoring is required but is so far unavailable.

In all the studied regions except for the west Kunlun Shan, most of the ice is stored in glaciers with more than 20% debris cover (Table 1, Supplementary Fig. S3), according to simple volume–area scaling[24]. Therefore, the response of debris-covered glaciers to climate change is of substantial importance for the evolution of discharge and water resources. Because supraglacial debris cover, with thicknesses exceeding a few centimetres, leads to a considerable reduction in melt rates[25,26], it slows a glacier's response to climate warming[18]. Debris cover also influences the impact of natural and anthropogenic forcings related to radiative heat transfer. Decadal to centennial variations in solar radiation[27] or atmospheric dust and soot deposition[28], for example, should have only minor mass-balance effects where thick debris cover is present. Such effects are probably greater in debris-free accumulation areas. But when accumulation areas are steep, as in the case of heavily debris-covered glaciers (Fig. 3a), snow avalanches redistribute large amounts of snow to lower elevations, where it is rapidly covered by thick blankets of debris.

Most of the available mass-balance records in the Himalaya are short (<10 yr), and at present only a few, small and mostly debris-free glaciers are regularly surveyed[7,8]. The spatial variability of glacier response to climate change renders extrapolation of the currently obtained mass-balance data to > 60,000 km^2 of glaciers in the greater Himalaya[8] problematic, particularly across different topographic and climatic regions. We suggest that the selection of benchmark glaciers for future mass balance studies should consider, beside climatic factors, also glacier size, topographic factors, and debris cover.

Debris-covered glaciers are not restricted to the Himalaya, but are common in many other mountain ranges around the world[7,18,19]. For realistic predictions of future water availability[9,10], and global sea-level change[11], debris cover and its influence on glacial-melt rates should be added to analyses that have determined glacier mass balances using data from mostly debris-free glaciers[8]. However, this requires more mass-balance studies from heavily debris-covered glaciers, inclusion of debris cover in glacier inventories, and adequate models covering large spatial scales that allow for the effect of debris cover, which are currently all missing.

Our study has shown that topographic factors, which usually vary considerably in mountainous terrain, have distinct effects on the response of glaciers to climate change. This implies caution when interpreting glacier frontal changes in a climatic sense[3,14].

Glacier frontal changes paired with flow velocity data allowed us to assess characteristic differences in the terminus dynamics of Himalayan glaciers. Although retreating glaciers dominate, retreat rates vary from high for debris-free glaciers to zero for glaciers with debris cover >20%. Such variations partly reflect topographic variations and associated differences in debris cover, but not necessarily different climate changes. In contrast, stable fronts of non-surging glaciers in the Karakoram are a strong indication of possibly different mass balances, and hence climatic changes, compared to their Himalayan neighbours.

Methods

We measured glacier-surface velocities from 2000 to 2008, based on sub-pixel cross-correlation of ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer) and SPOT (Satellite Pour l'Observation de la Terre) satellite images (Supplementary Table S1,S2) with the program COSI-Corr (ref. 29) and following the procedures outlined in ref. 16. In brief, two scenes taken at different times are orthorectified, co-registered and correlated, and the horizontal displacement of glacier-surface features is recorded every 60 m. We studied any glacier within twelve heavily ice-covered areas in the greater Himalayan realm where data coverage allows construction of a continuous velocity profile along the trunk glacier without significant data gaps. Surface velocities were obtained along the central flowline, which we identified manually, based on the satellite images and the velocity maps (Supplementary Fig. S1). We excluded surging glaciers from our analysis, which alternate between usually rapid advances and longer periods of slow retreat and/or stability.

The extent of debris cover was determined based on digitized glacier outlines combined with the distribution of clean ice and snow at the end of the hydrological year, which we obtained from Landsat Thematic Mapper (TM) band TM4/TM5-ratio images (Supplementary Fig. S1, Table S3). We measured changes in glacier area at the terminus from the orthorectified 15-m resolution ASTER images. Combined with glacier widths we calculated mean annual advance or retreat rates during the period of investigation (Supplementary Table S5). We estimated mapping inaccuracies by comparing several ASTER-based area changes with those obtained from 5-m resolution SPOT images (Supplementary Table S2). Deviations of mean annual frontal changes are on average $\sim 5\,m\,yr^{-1}$, and up to $\sim 20\,m\,yr^{-1}$ in the case of one heavily debris-covered glacier. Here, we assume a uniform uncertainty of $\sim 10\,m\,yr^{-1}$ for all studied glaciers, which is probably a conservative estimate. We manually identified snowlines, the boundary between bright snow and darker ice, in satellite images taken at the end of the hydrological year, to define accumulation areas, and calculated mean slope angles with a void-filled digital elevation model (DEM). We measured the slope of the ice surface in the terminus regions along the profile that follows the central flowline.

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References

1. Cruz, R. V. *et al.* in *IPCC Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* (eds Parry, M. L. *et al.*) 469–506 (Cambridge Univ. Press, 2007).
2. Cogley, J. G., Kargel, J. S., Kaser, G. & Van der Veen, C. J. Tracking the source of glacier misinformation. *Science* **337,** 522 (2010).
3. Raina, V. K. Himalayan glaciers. A state-of-art review of glacial studies, glacial retreat and climate change. Ministry of Environment and Forests, India. http://go.nature.com/pLgJ6D (2009).
4. Hewitt, K. The Karakoram anomaly? Glacier expansion and the 'elevation effect', Karakoram Himalaya. *Mt. Res. Dev.* **25,** 332–340 (2005).
5. Ageta, Y. *et al.* in *Debris-covered Glaciers* (eds Nakawo, M., Raymond, C. F. & Fountain, A.) 165–175 (IAHS Publ. 264, 2000).
6. Fujita, K., Nakawo, M., Fujii, Y. & Paudyal, P. Changes in glaciers in Hidden Valley, Mukut Himal, Nepal Himalayas, from 1974 to 1994. *J. Glaciol.* **43,** 583–588 (1997).
7. U.N. Environmental Program and World Glacier Monitoring Service, *Global Glacier Change: Facts and Figures* UNEP Publ., http://www.grid.unep.ch/glaciers/ (2008).
8. Dyurgerov, M. B. & Meier, M. F. *Glaciers and the Changing Earth System: A 2004 Snapshot*. (Occas. Pap., 58, Inst. of Arct. And Alp. Res. 2005).
9. Rees, H. G. & Collins, D. N. Regional differences in response of flow in glacier-fed Himalayan rivers to climatic warming. *Hydrol. Process.* **20,** 2157–2169 (2006).
10. Immerzeel, W. W., van Beek, L. P. H. & Bierkens, M. F. P. Climate change will affect the Asian water towers. *Science* **328,** 1382–1385 (2010).
11. Raper, S. C. B. & Braithwaite, R. J. Low sea level rise projections from mountain glaciers and icecaps under global warming. *Nature* **439,** 311–313 (2006).
12. Barnett, T. P., Adam, J. C. & Lettenmaier, D. P. Potential impacts of a warming climate on water availability in snow-dominated regions. *Nature* **439,** 303–309 (2005).
13. Bookhagen, B. & Burbank, D. W. Towards a complete Himalayan hydrologic budget: The spatiotemporal distribution of snow melt and rainfall and their impact on river discharge. *J. Geophys. Res.* **115,** F03019 (2010).
14. Oerlemans, J. Extracting a climate signal from 169 glacier records. *Science* **308,** 675–677 (2005).
15. Quincey, D. J., Luckman, A. & Benn, D. I. Quantification of Everest region glacier velocities between 1992 and 2002, using satellite radar interferometry and feature tracking. *J. Glaciol.* **55,** 596–606 (2009).
16. Scherler, D., Leprince, S. & Strecker, M. R. Glacier-surface velocities in alpine terrain from optical satellite imagery—accuracy improvement and quality assessment. *Remote Sens. Environ.* **112,** 3806–3819 (2008).
17. Bolch, T., Buchroithner, M., Pieczonka, T. & Kunert, A. Planimetric and volumetric glacier changes in the Khumbu Himal, Nepal, since 1962 using Corona, Landsat TM and ASTER data. *J. Glaciol.* **54,** 592–600 (2008).
18. Ogilvie, I. H. The effect of superglacial débris on the advance and retreat of some Canadian glaciers. *J. Geol.* **12,** 722–743 (1904).
19. Kirkbride, M. P. The temporal significance of transitions from melting to calving termini at glaciers in the central Southern Alps of New Zealand. *Holocene* **3,** 232–240 (1993).
20. Ouimet, W., Whipple, K. & Granger, D. Beyond threshold hillslopes: Channel adjustment to base-level fall in tectonically active mountain ranges. *Geology* **37,** 579–582 (2009).
21. Archer, C. L. & Caldeira, K. Historical trends in the jet streams. *Geophys. Res. Lett.* **35,** L08803 (2008).
22. Treydte, K. S. *et al.* The twentieth century was the wettest period in northern Pakistan over the past millennium. *Nature* **440,** 1179–1182 (2006).
23. Fowler, H. J. & Archer, D. R. Conflicting signals of climatic change in the upper Indus basin. *J. Clim.* **19,** 4276–4293 (2006).
24. Bahr, D. B., Meier, M. F. & Peckham, S. D. The physical basis of glacier volume–area scaling. *J. Geophys. Res.* **102,** 20,355–20,362 (1997).
25. Mattson, L. E., Gardner, J. S. & Young, G. J. in *Snow and Glacier Hydrology* (ed. Young, G. J.) 289–296 (IAHS Publ. 218, 1993).
26. Østrem, G. Ice melting under a thin layer of moraine, and the existence of ice cores in moraine ridges. *Geogr. Ann.* **41,** 228–230 (1959).
27. Huss, M., Funk, M. & Ohmura, A. Strong Alpine glacier melt in the 1940s due to enhanced solar radiation. *Geophys. Res. Lett.* **36,** L23501 (2009).
28. Xu, B. *et al.* Black soot and the survival of Tibetan glaciers. *Proc. Natl Acad. Sci. USA* **106,** 22114–22118 (2009).
29. Leprince, S., Barbot, S., Ayoub, F. & Avouac, J-P. Automatic and precise orthorectification, coregistration, and subpixel correlation of satellite images, application to ground deformation measurements. *IEEE Trans. Geosci. Remote Sensing* **45,** 1529–1558 (2007).

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Author contributions

D.S. designed the study and conducted all analyses. All authors contributed to discussions, interpretations and writing the paper.

Additional information

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