nature geoscience

LETTERS

PUBLISHED ONLINE: 15 APRIL 2012 | DOI: 10.1038/NGEO1450

Slight mass gain of Karakoram glaciers in the early twenty-first century

Julie Gardelle[1]*, Etienne Berthier[2] and Yves Arnaud[3]

Assessments of the state of health of Hindu-Kush-Karakoram-Himalaya glaciers and their contribution to regional hydrology and global sea-level rise suffer from a severe lack of observations[1]. The globally averaged mass balance of glaciers and ice caps is negative[1-3]. An anomalous gain of mass has been suggested for the Karakoram glaciers[2,4-6], but was not confirmed by recent estimates of mass balance. Furthermore, numerous glacier surges in the region that lead to changes in glacier length and velocity[7-11] complicate the interpretation of the available observations. Here, we calculate the regional mass balance of glaciers in the central Karakoram between 1999 and 2008, based on the difference between two digital elevation models. We find a highly heterogeneous spatial pattern of changes in glacier elevation, which shows that ice thinning and ablation at high rates can occur on debris-covered glacier tongues. The regional mass balance is just positive at $+0.11\pm0.22\,\mathrm{m\,yr^{-1}}$ water equivalent and in agreement with the observed reduction of river runoff that originates in this area[12]. Our measurements confirm an anomalous mass balance in the Karakoram region and indicate that the contribution of Karakoram glaciers to sea-level rise was $-0.01\,\mathrm{mm\,yr^{-1}}$ for the period from 1999 to 2008, $0.05\,\mathrm{mm\,yr^{-1}}$ lower than suggested before[13].

The Karakoram mountain range, at the west end of the Himalayan arc, is covered by $\sim$19,950 km^2 of glaciers[4]. Even though glaciological studies are scarce in this region, owing to remoteness and political issues, it seems that during the past three decades Karakoram glaciers did not follow the global trend of glacial decline[2]. Analysis of satellite imagery over six regions spread along the Hindu-Kush–Karakoram–Himalaya (HKKH) revealed that, in contrast to the central and eastern Himalaya where most glaciers were retreating, more than 50% of Karakoram glaciers were advancing or stable between 2000 and 2008 (ref. 6). Furthermore, Fujita and Nuimura[14] reported a descending trend in the modelled equilibrium-line altitude in the Karakoram during 1976–1995. The gradual acceleration of the ice flow of non-surging Baltoro Glacier during the 2000s is another sign of a stable or growing glacier[15]. These results, although they indirectly indicate a possible mass gain or an equilibrium state for glaciers in the region, are difficult to interpret because of the occurrence of surges and complex glacier behaviours[5,7]. For example, the equilibrium-line altitude and its temporal variations may not be readily interpreted in terms of glacier health[16], particularly on surge-type glaciers. Hence, the existence of a Karakoram anomaly remains controversial and deserves urgent attention[4]. In this context, mass-balance data are needed to assess the state of health of Karakoram glaciers and constrain their contribution to sea-level rise[1,3].

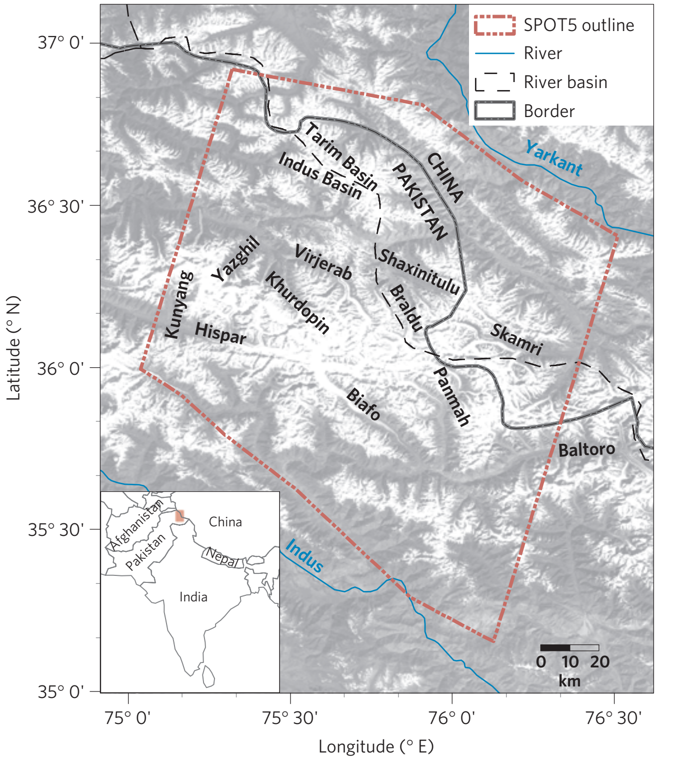

Figure 1 | Study area in central Karakoram. The red dashed line denotes the extent of the SPOT5 DEM. The background image is a Landsat Enhanced Thematic Mapper panchromatic mosaic (© USGS 2002). The names of the main glaciers are also given.

Here, we observe the geodetic mass balance for a 5,615 km^2 ice-covered area in the central Karakoram (Fig. 1), study its spatial variability and estimate the corresponding sea-level rise contribution. We measured regional changes in ice elevation by differencing two digital elevation models (DEMs) generated from the February 2000 Shuttle Radar Topographic Mission (SRTM) and from Satellite Pour l'Observation de la Terre (SPOT5) optical stereo imagery acquired in December 2008. Mean elevation changes are then converted into mass balance by assuming a density of $900\,\mathrm{kg\,m^{-3}}$ both in the accumulation and ablation areas. This assumption, derived from Sorge's law[17], is valid if the density vertical profile remains unchanged during the study period.

It is crucial to ensure that all systematic biases potentially affecting the DEMs have been removed before computing the glacier mass balance. This includes the correction of horizontal shifts between

[1]CNRS—Université Grenoble 1, LGGE UMR 5183, 54 rue Molière, Domaine Universitaire, BP 96, 38402 Saint Martin d'Hères Cedex, France, [2]CNRS, Université de Toulouse, LEGOS, 14 avenue Edouard Belin, Toulouse 31400, France, [3]IRD—Université Grenoble 1, LTHE UMR 5564/LGGE UMR 5183, 54 rue Molière, Domaine Universitaire, BP 96, 38402 Saint Martin d'Hères Cedex, France. *e-mail: gardelle@lgge.obs.ujf-grenoble.fr.

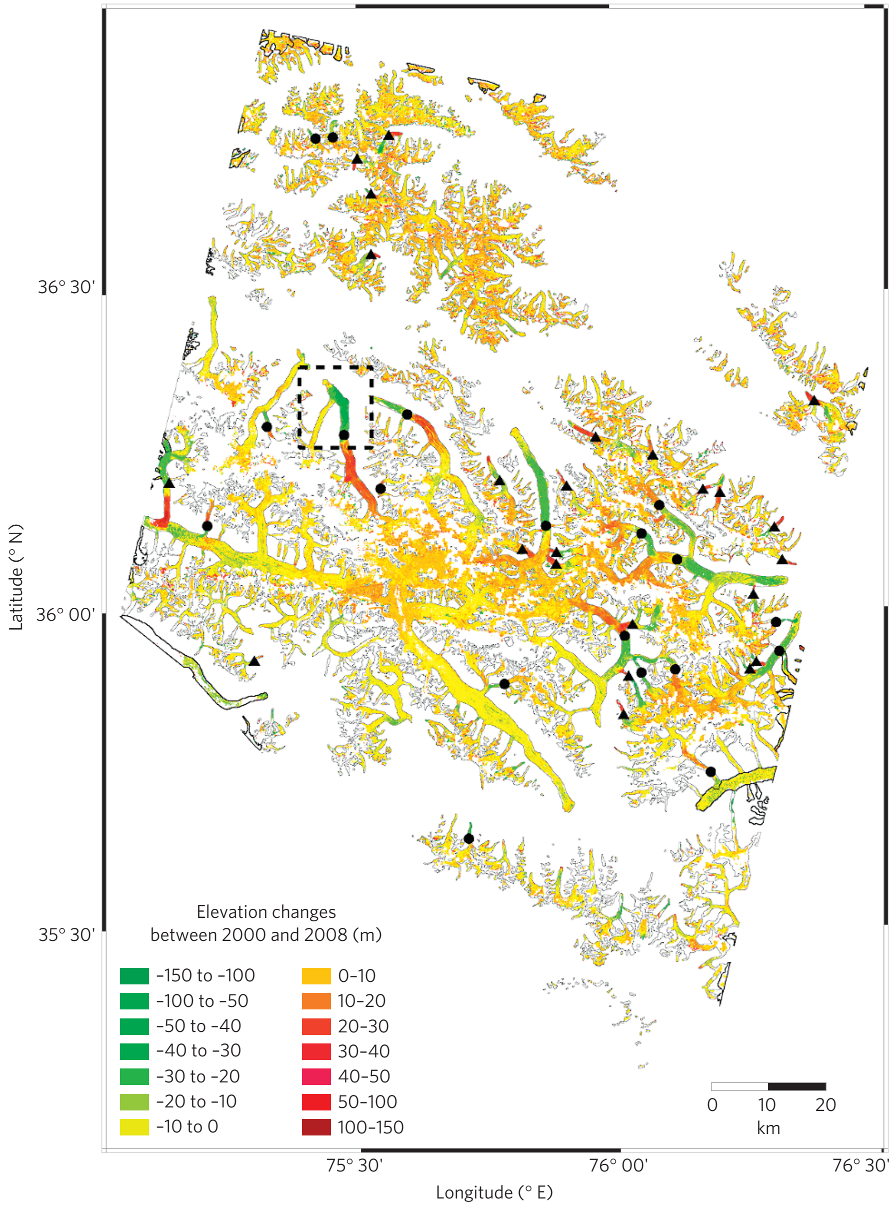

Figure 2 | Map of glacier elevation changes between February 2000 and December 2008. Grey polygons correspond to the glacier outlines (thick black polygons correspond to edge glaciers that were excluded from the mass-balance computation). The total ice-covered area is 5,615 km^2. The black triangles represent glaciers in a surge phase; black circles represent glaciers in a post-surge or quiescent phase. The dashed black box defines the area shown in Supplementary Fig. S1. 41% of elevation changes do not exceed ±5 m. Elevation differences off-glaciers are shown in Supplementary Fig. S4.

the DEMs, along/across-track or elevation-dependent biases, as well as C-band penetration into snow and ice in the case of the SRTM DEM and a seasonality correction to cover nine full 12-month periods from December 1999 to December 2008 (see the Methods section).

The mean annual glacier mass balance between 1999 and 2008 is positive, $+0.11 \pm 0.22\ m\,yr^{-1}$ water equivalent (w.e.) and nearly identical for non-surging ($+0.10 \pm 0.19\ m\,yr^{-1}$ w.e.) and surge-type glaciers ($+0.11 \pm 0.31\ m\,yr^{-1}$ w.e.). If we assume that in the accumulation area, only firn (density of $600\ kg\,m^{-3}$) is lost or gained, the total mass balance drops to $+0.05 \pm 0.16\ m\,yr^{-1}$ w.e. Thus, for two extreme-density scenarios, the regional glacier mass balance is always close to zero, so that the assumption that Sorge's law holds has little impact on the main result, which is that Karakoram glaciers were close to equilibrium during 1999–2008.

The spatial distribution of elevation changes is far from homogeneous, as many glaciers (depicted with circles and triangles in Fig. 2) show strong thinning and thickening rates (up to $16\ m\,yr^{-1}$ in both cases). The glaciers experiencing these unusual spatial patterns are surge-type glaciers. Many of them are known or suspected to have surged in the past[7–11] and exhibit morphological features characteristic of surges (for example, contorted moraines[7]), as well as high velocities[9,10]. Among surge-type glaciers, we distinguish two categories: first, glaciers with high thickening rates in the lower part of their ablation area and high thinning rates in their upper part (triangles in Fig. 2) that surged between 2000 and 2008; and second, glaciers thickening in their upper part and thinning in their lower ablation area (circles in Fig. 2) that surged before 2000 and are now in a quiescent (or post-surge) phase.

Elevation changes with altitude for selected individual glaciers are shown in Fig. 3 for surging and quiescent glaciers, as well as non-surging glaciers for comparison. Elevation changes on surging and quiescent glaciers exhibit sinusoidal excursions of similar shape but opposite sign on the glacier tongue and are damped in the upper

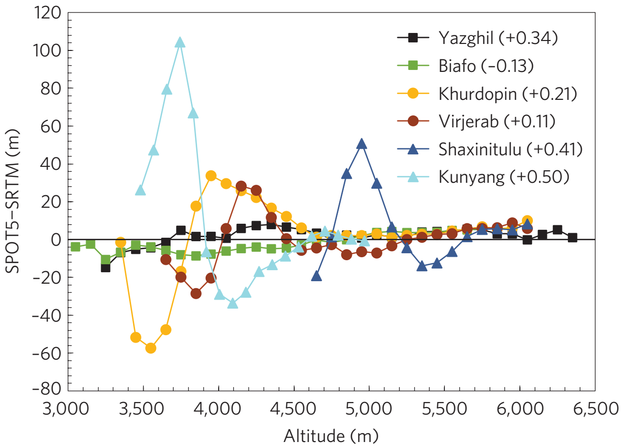

Figure 3 | Elevation changes with altitude between February 2000 and December 2008 for selected surge-type and non-surging glaciers. We plotted: two glaciers that surged between 2000 and 2008 (triangles); two glaciers in their quiescent phase between 2000 and 2008 that surged before 2000 (circles); and two non-surging glaciers (squares). Error bars are not shown for clarity but range between ±0.25 m and ±17.24 m (mean error of ±2.72 m). The location of each glacier is given in Fig. 1. Numbers in the legend correspond to the glacier-wide mass balances (m yr^{-1} w.e.).

part of the glacier. In most cases, the surge wave does not reach the glacier terminus and does not impact the upper accumulation area, as noticed also by Quincey and colleagues[10].

In ablation areas of non-surging glaciers, between 3,000 m and 5,000 m, the mean rate of elevation change under debris (−0.48 m yr^{-1}) is similar to that over clean ice and snow (−0.49 m yr^{-1}). These rates are computed on pixel samples that have comparable altitude distributions, that is, pixels are randomly selected so that altitude histograms are similar over debris and clean ice. This finding seems to contradict the common assumption[18] that debris cover has a protective effect, which should lead to a higher thinning rate over clean ice. Two hypotheses could explain this counter-intuitive observation. First, the surface ablation may be higher than previously thought on debris-covered glacier tongues due to several factors (thin debris layers, meltwater ponds[19] and exposed ice cliffs) that are known to enhance tongue-wide ablation. Such factors do not act on the very local scale (a few square centimetres around an ablation stake) where the insulating effect of debris has been measured[18]. For example, we infer area-average ablation rates as high as 6.2 m yr^{-1} (at least) on the debris-covered Khurdopin glacier tongue during 2000–2008 (Supplementary Information and Supplementary Fig. S1). We note that this glacier ended its last surge in 1999 (ref. 10) and presented a rough and heavily crevassed surface in the early 2000s that may have favoured enhanced ice ablation on the tongue. Further work is thus needed to assess whether similarly high tongue-wide ablation rates are also experienced by non-surging debris-covered glaciers. A second hypothesis could be that most of the debris-covered glacier tongues in the Karakoram exhibit a slower flow than debris-free ones, so that surface ablation is balanced only by the small ice flux from upstream.

The slightly positive mass balance during 1999–2008 in the Karakoram contrasts with the negative global average[1–3] and the few mass-balance values available in the rest of the HKKH range[14,20–23], which are negative over the past decades. Recent glacier expansion[5] and speed-up over the region[15,24] tally with the gain of mass calculated in this study. Some hydrological variables, indirectly linked to glacier mass balance, also agree with the observation of glacier stability in the Karakoram. Fowler and Archer[12] reported a 20% decrease in runoff for the Hunza and Shyok rivers (which originate in the Karakoram) between 1961 and 2000. Although their study period precedes ours, it reveals unusual climatic trends in the Karakoram, compared with the rest of the HKKH. Tahir *et al.*[25] measured an increase in snow cover between 2000 and 2009 over the Hunza Basin, which would be consistent with a positive mass balance of Karakoram glaciers. The studies using the Gravity Recovery and Climate Experiment project data to infer the change in glacier mass in central Asia led to conflicting results discussed in the Supplementary Information.

The interpretation of this now confirmed Karakoram anomaly is complicated by the lack of long-term programmes of field mass balance and the scarcity of near-glacier, up-to-date climate data. However, the climatic trends observed on valley floors (below 2,000 m) above sea level during the last decades of the twentieth century can provide a first clue. Archer and Fowler[26] reported an increase in winter precipitation since 1961, which is a potential source for greater accumulation in the upper parts of glaciers[5,10,15] and can explain the glacier thickening measured above 5,300 m above sea level (Supplementary Fig. S2). Furthermore, between 1961 and 2000, mean summer temperature declined at all climate stations[12], probably resulting in a decreasing glacier melt.

The sea-level rise contribution for Karakoram glaciers during the past decade has been previously estimated using spatial extrapolation of the negative mass balances (range: −0.6 to −0.8 m yr^{-1} w.e.) observed only in the central and eastern parts of the HKKH (ref. 13). Our conclusion that Karakoram glaciers had a small mass gain at the beginning of the twenty-first century indicates that those central/eastern glaciers are not representative of the whole HKKH. Assuming that the glaciers studied here are representatitve of the whole Karakoram region (Supplementary Fig. S3), we suggest that the sea-level-rise contribution for this region during the first decade of the twenty-first century should be revised from +0.040 mm yr^{-1} (as estimated by Church *et al.*[13]) to −0.006 mm yr^{-1} sea-level equivalent.

Methods

Planimetric and vertical adjustment. First, horizontal shifts between the DEMs must be corrected to avoid systematic biases according to terrain aspect[27]. The planimetric adjustment is done by minimizing the root mean square error of elevation differences between the two DEMs on stable areas (that is a 1,180 km^2 area off-glaciers, where the terrain is assumed to experience negligible elevation changes)[20]. In our case, the shift applied to coregister the SRTM DEM to the SPOT5 DEM was −0.26 and −0.16 pixels, respectively, in easting and northing. After the planimetric adjustment, the off-glacier elevation difference (mean ± standard deviation, σ) evolved from 0.6±9.8 m to 0.5±9.2 m.

The remaining systematic biases are also investigated off-glaciers. A bias related to the SPOT5 acquisition geometry in the cross-track and along-track direction was corrected by fitting a fifth-order polynomial to the elevation differences off-glaciers[27]. We also investigated the issue of elevation-dependent biases[28]. Part of this bias was first removed based on the relation off-glacier between elevation differences and the terrain maximum curvature[28]. The remaining part was investigated using an additional DEM, acquired in X-band during the same mission as the SRTM C-band. By comparing the SRTM X-band and the SRTM C-band DEMs over glaciers, and assuming that the X-band radar penetration into snow and ice is negligible, it is possible to estimate and correct the C-band radar penetration[28] for each glacier pixel according to its elevation. The mean C-band snow and ice penetration over central Karakoram is 3 m with values up to 8 m in the accumulation areas. SRTM X-band was not used in the first place to compute elevation changes because of its incomplete spatial coverage (only 27% of our study area) owing to a narrower swath.

The planimetric adjustment had only a small impact on the final mass balance (correction of −0.02 m yr^{-1} w.e., Supplementary Table S1), whereas the C-band-penetration correction had the greatest influence (correction of −0.29 m yr^{-1} w.e.). Given the magnitude of the C-band-penetration correction, we stress that C-band (and X-band) radar penetration on mountain glacier ice, firn and snow should receive more attention in the near future, in particular with the forthcoming release of the DEMs from the German Aerospace Center (DLR) Tandem-X mission.

The resulting map of elevation differences on stable areas after adjusting the DEMs horizontally and vertically is given in Supplementary Fig. S4. The standard deviation of the elevation differences dropped from 9.8 m to 8.4 m after all adjustments. The distribution of elevation differences off-glaciers is nearly Gaussian (Supplementary Fig. S5).

Elevation changes and mass-balance computation. Pixels interpolated in at least one of the DEMs (40% of the ice-covered areas) are excluded as well as the 0.1% of pixels where elevation difference exceeds ±150 m. Furthermore, glacier parts that are truncated at the edge of the SPOT5 DEM (Fig. 2) are not included in the mass-balance analysis. Surge-type glaciers are identified both from the literature[8,11] and their characteristic patterns of elevation changes, to process them separately. Elevation changes on non-surging glaciers are averaged for altitude intervals of 100 m. The histograms of elevation change for each altitude range are given in Supplementary Fig. S6 and show that the changes in glacier elevation are homogeneous at a given altitude, following a nearly Gaussian distribution. Pixels for which the absolute elevation difference is larger than 3 σ are considered as outliers and excluded from subsequent analysis[29]. The same procedure (averaging for altitude bands of 100 m and filtering of 3 σ) is applied separately to each surge-type glacier. Hence, the regional mass balance is the area-weighted sum of the mass balance of all non-surging glaciers and the mass balance of each surge-type glacier. Glacier volume changes over void-filled regions of SPOT5 or SRTM DEMs were estimated assuming that void-filled pixels experienced the mean elevation change of measurable pixels in the same altitude interval. This value was added to the measured changes to obtain a total volume change in each region.

Above 6,400 m, the number of glacier pixels is too small to compute significant mean elevation changes. However, the percentage of the glacier area above this altitude is only 0.6% (Supplementary Fig. S2). The thickness changes as a function of altitude for non-surging glaciers are also given in Supplementary Fig. S2.

As the SRTM DEM (now corrected for C-band penetration into ice and snow) maps the glacier surface in February 2000, an estimation of the mass that accumulated between December 1999 and February 2000, 0.26 m w.e. according to accumulation measurements on Biafo Glacier between 1985 and 1986 (ref. 30), is subtracted. Thus, our corrected geodetic mass balance covers nine full years between December 1999 and December 2008.

A detailed accuracy assessment of the elevation changes is given in the Supplementary Information.

Received 10 November 2011; accepted 19 March 2012; published online 15 April 2012

References

1. Kaser, G., Cogley, J. G., Dyurgerov, M. B., Meier, M. F. & Ohmura, A. Mass balance of glaciers and ice caps: consensus estimates for 1961–2004. *Geophys. Res. Lett.* **33,** L19501 (2006).
2. Zemp, M., Hoelzle, M. & Haeberli, W. Six decades of glacier mass-balance observations: A review of the worldwide monitoring network. *Ann. Glaciol.* **50** (50), 101–111 (2009).
3. Cogley, J. G. Geodetic and direct mass-balance measurements: Comparison and joint analysis. *Ann. Glaciol.* **50** (50), 96–100 (2009).
4. Cogley, J. G. Present and future states of Himalaya and Karakoram glaciers. *Ann. Glaciol.* **52** (59), 69–73 (2011).
5. Hewitt, K. The Karakoram anomaly? Glacier expansion and the 'elevation effect', Karakoram Himalaya. *Mt. Res. Dev.* **25,** 332–340 (2005).
6. Scherler, D., Bookhagen, B. & Strecker, M. R. Spatially variable response of Himalayan glaciers to climate change affected by debris cover. *Nature Geosci.* **4,** 156–159 (2011).
7. Hewitt, K. Tributary glacier surges: An exceptional concentration at Panmah Glacier, Karakoram Himalaya. *J. Glaciol.* **53,** 181–188 (2007).
8. Barrand, N. E. & Murray, T. Multivariate controls on the incidence of glacier surging in the Karakoram Himalaya. *Arct. Antarct. Alp. Res.* **38,** 489–498 (2006).
9. Copland, L. *et al.* Glacier velocities across the central Karakoram. *Ann. Glaciol.* **50** (52), 41–49 (2009).
10. Quincey, D. J. *et al.* Karakoram glacier surge dynamics. *Geophys. Res. Lett.* **38,** L18504 (2011).
11. Copland, L. *et al.* Expanded and recently increased glacier surging in the Karakoram. *Arct. Antarct. Alp. Res.* **43,** 503–516 (2011).
12. Fowler, H. J. & Archer, D. R. Conflicting signals of climatic change in the Upper Indus Basin. *J. Clim.* **19,** 4276–4293 (2006).
13. Church, J. A. *et al.* Revisiting the Earth's sea-level and energy budget from 1961 to 2008. *Geophys. Res. Lett.* **38,** L18601 (2011).
14. Fujita, K. & Nuimura, T. Spatially heterogeneous wastage of Himalayan glaciers. *Proc. Natl Acad. Sci. USA* **108,** 14011–14014 (2011).
15. Quincey, D. J. *et al.* Ice velocity and climate variations for Baltoro Glacier, Pakistan. *J. Glaciol.* **55,** 1061–1071 (2009).
16. Hewitt, K. Glacier change, concentration, and elevation effects in the Karakoram Himalaya, Upper Indus Basin. *Mt. Res. Dev.* **31,** 188–200 (2011).
17. Bader, H. Sorge's law of densification of snow on high polar glaciers. *J. Glaciol.* **2,** 319–323 (1954).
18. Mattson, L. E., Gardner, J. S. & Young, G. J. in *Snow and Glacier Hydrology* (ed. Young, G. J.) 289–296 (IAHS Publ. 218, 1993).
19. Sakai, A., Takeuchi, N., Fujita, K. & Nakawo, M. in *Debris-Covered Glaciers* (eds Nakawo, M., Raymond, C. F. & Fountain, A.) 119–130 (IAHS Publ. 264, 2000).
20. Berthier, E. *et al.* Remote sensing estimates of glacier mass balances in the Himachal Pradesh (Western Himalaya, India). *Remote Sens. Environ.* **108,** 327–338 (2007).
21. Bhutiyani, M. R. Mass-balance studies on Siachen Glacier in the Nubra valley, Karakoram Himalaya, India. *J. Glaciol.* **45,** 112–118 (1999).
22. Bolch, T., Pieczonka, T. & Benn, D. I. Multi-decadal mass loss of glaciers in the Everest area (Nepal Himalaya) derived from stereo imagery. *Cryosphere* **5,** 349–358 (2011).
23. Azam, M. F. *et al.* From balance to imbalance: A shift in the dynamic behaviour of Chhota Shigri Glacier (Western Himalaya, India). *J. Glaciol.* **58,** 315–324 (2012).
24. Heid, T. & Kääb, K. Worldwide widespread decadal-scale decrease of glaciers speed revealed using repeat optical satellite images. *Cryosphere Discuss.* **5,** 3025–3051 (2011).
25. Tahir, A. A., Chevallier, P., Arnaud, Y. & Ahmad, B. Snow cover dynamics and hydrological regime of the Hunza River Basin, Karakoram Range, Nothern Pakistan. *Hydrol. Earth Syst. Sci.* **15,** 2275–2290 (2011).
26. Archer, D. R. & Fowler, H. J. Spatial and temporal variations in precipitation in the Upper Indus Basin, global teleconnections and hydrological implications. *Hydrol. Earth Syst. Sci.* **8,** 47–61 (2004).
27. Nuth, C. & Kääb, A. Co-registration and bias corrections of satellite elevation data sets for quantifying glacier thickness change. *Cryosphere* **5,** 271–290 (2011).
28. Gardelle, J., Berthier, E. & Arnaud, Y. Impact of resolution and radar penetration on glacier elevation changes computed from DEM differencing. *J. Glaciol.* **58,** 419–422 (2012).
29. Berthier, E., Arnaud, Y., Baratoux, D, Vincent, C. & Rémy, F. Recent rapid thinning of the 'Mer de Glace' glacier derived from satellite optical images. *Geophys. Res. Lett.* **31,** L17401 (2004).
30. Wake, C.P. Glaciochemical investigations as a tool for determining the spatial and seasonal variation of snow accumulation in the central Karakoram, northern Pakistan. *Ann. Glaciol.* **13,** 279–284 (1989).

Acknowledgements

J.G. acknowledges a PhD fellowship from the French Space Agency (CNES) and the French National Research Center (CNRS). E.B. acknowledges support from CNES through the TOSCA and ISIS proposal no. 397 and from the Programme National de Télédétection Spatiale. We thank the United States Geological Survey for allowing free access to their Landsat archive, CIAT for SRTM C-band data and DLR for SRTM X-band data. We thank A. Kääb for his comments on an earlier version of the manuscript and G. Cogley for a constructive review.

Author contributions

J.G. led the development of this study, carried out all DEM analysis and led the writing of the manuscript. Y.A. and E.B. initiated the study and contributed to the development of the methodology, discussion of results and the writing of the manuscript.

Additional information

The authors declare no competing financial interests. Supplementary information accompanies this paper on www.nature.com/naturegeoscience. Reprints and permissions information is available online at www.nature.com/reprints. Correspondence and requests for materials should be addressed to J.G.