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Mass gain of glaciers in Lahaul and Spiti region (North India) during the nineties revealed by in-situ and satellite geodetic measurements

C. Vincent[1], A. Ramanathan[2], P. Wagnon[3], D. P. Dobhal[4], A. Linda[2], E. Berthier[5], P. Sharma[6], Y. Arnaud[3], M. F. Azam[2,3], P. G. Jose[2], and J. Gardelle[1]

[1]UJF – Grenoble 1/CNRS, Laboratoire de Glaciologie et Géophysique de l'Environnement (LGGE) UMR5183, Grenoble, 38041, France
[2]School of Environmental Sciences, Jawaharlal Nehru University, New Delhi 110067, India
[3]IRD/UJF – Grenoble 1/CNRS/G-INP, LGGE UMR5183, LTHE UMR5564, Grenoble, 38402, France
[4]Wadia Institute of Himalayan Geology, Dehra Dun 248 001, India
[5]CNRS, Université de Toulouse, LEGOS, 14 av. Ed. Belin Toulouse, 31400, France
[6]National Centre for Antarctic and Ocean Research, Headland Sada, Goa 403804, India

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Correspondence to: P. Wagnon (patrick.wagnon@ujf-grenoble.fr)

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Abstract

The volume change of Chhota Shigri Glacier (India, 32° N) between 1988 and 2010 has been determined using in-situ geodetic measurements. This glacier has experienced only a slight mass loss over the last 22 yr (−3.8 ± 1.8 m w.e.). Using satellite digital elevation models (DEM) differencing and field measurements, we measure a negative mass balance (MB) between 1999 and 2011 (−4.7 ± 1.8 m w.e.). Thus, we deduce a positive MB between 1988 and 1999 (+1.0 ± 2.5 m w.e.). Furthermore, satellite DEM differencing reveals a good correspondence between the MB of Chhota Shigri Glacier and the MB of an over 2000 km^2 glaciarized area in the Lahaul and Spiti region during 1999–2011. We conclude that there has been no large ice wastage in this region over the last 22 yr, ice mass loss being limited to the last decade. This contrasts to the most recent compilation of MB data in the Himalayan range that indicates ice wastage since 1975, accelerating after 1990. For the rest of western Himalaya, available observations of glacier MBs are too sparse and discontinuous to provide a clear and relevant regional pattern of glacier volume change over the last two decades.

1 Introduction

Glaciers have been recognized as good climatic indicators (e.g. Oerlemans, 2001), especially in high remote areas such as the Himalayas where meteorological observations are difficult and thus only recent and sparse (e.g. Shekhar et al., 2010). Moreover, understanding the fluctuations of Himalayan glaciers is of great interest for diagnosing the future water availability in these highly populated watersheds (Kaser et al., 2010; Immerzeel et al., 2010; Thayyen and Gergan, 2010). Unfortunately, data on recent glacier fluctuations are sparse and even sparser as we go back in time (Cogley, 2011; Bolch et al., 2012) and thus, the rate at which these glaciers are shrinking remains poorly constrained. Most field-based measurements in the Himalayas over recent decades concern changes in glacier length or area for a limited number of glaciers

(Dyurgerov and Meier, 2005; Cogley, 2009, 2011; Kargel et al., 2011; WGMS, 2011). Remote sensing provides regional data for numerous glaciers over the last 3 decades, but these data are also mostly limited to glacier length/area variations (e.g. Scherler et al., 2011; Bhambri et al., 2011). However, these length and area variations cannot be directly interpreted as direct indicators of climate change on an annual or decadal time-scale due to the lag in the response time of glaciers (Cuffey and Paterson, 2010) and because most of these glaciers are covered by debris that strongly affects the relationship between the surface energy balance and melting (Fujita and Nuimura, 2011). Moreover, snout fluctuations obtained from satellite or aerial images are subject to uncertainty due to difficulties in delineating debris-covered glacier tongues, which are not easily identifiable on images. For these reasons, glacier trends obtained from snout fluctuations alone in the Himalayas provide only a partial picture of glacier variability (Raina, 2009). The best indicator of climate change is the glacier-wide mass balance (MB) which results mainly from climate variables such as solid precipitation and heat and radiative fluxes via ablation (Oerlemans, 2001) providing that the MB is measured on a surface free of debris.

The MB can be obtained directly using the geodetic method (elevation changes measured over the whole glacier area) or the glaciological method (Cuffey and Paterson, 2010). Recent studies (Berthier et al., 2007; Bolch et al., 2011; Gardelle et al., 2012a; Nuimura et al., 2012) provide volumetric MBs for numerous glaciers in the Himalayas using satellite stereo-imagery, but generally with larger uncertainties than those obtained using in-situ measurements when a single glacier is considered. Satellite laser altimetry provides sparse but accurate measurements of elevation changes along the whole mountain range but is restricted to the 2003–2008 time interval (Kääb et al., 2012). Moreover, very few continuous direct MB observations using the glaciological method are available in the Himalayas. Figure 1 shows the locations of these surveyed glaciers in the western Himalaya, a region which includes roughly one third of all Himalayan glaciers, representing a total ice-covered area of 9200 km^2 (all glaciers of northern India between Pakistan and Nepal, except the Indian Karakoram, north of

Indus River) (Bajracharya and Shrestha, 2011). The western Himalaya has an approximate length of 700 km extending from the limit of Karakoram in the north-west to the Nepal border in the south-east. The MB series obtained by the glaciological method in this region are listed in Table 1.

One of the longest continuous series, initiated however only since 2002, comes from Chhota Shigri Glacier in India (Wagnon et al., 2007; Azam et al., 2012). In this paper, we extend the Chhota Shigri MBs back to 1988 using in-situ geodetic measurements performed in 1988 and 2010. In addition, we assess whether Chhota Shigri Glacier is representative of the whole Lahaul and Spiti region using ice elevation changes measured between 1999 and 2011 using digital elevation models (DEM) derived from spaceborne sensors. Finally, we compile field data available from other glaciers to obtain an up-to-date overview of glacier fluctuations in the western Himalaya over recent decades.

2 Site description, data and methodology

2.1 Site description

Chhota Shigri Glacier (32.2° N, 77.5° E) is a valley-type glacier located in the Chandra-Bhaga river basin of Lahaul and Spiti valley, Pir Panjal range, Western Himalaya. Its surface area is 15.7 km^2 and it is 9 km long. It extends from 6263 to 4050 m a.s.l. This glacier is mainly free of debris with only 3.4 % of the total glacier area covered with debris. The altitude of the equilibrium line for a zero net balance is close to 4900 m a.s.l. (Wagnon et al., 2007). It lies in a region alternatively influenced by the Indian Monsoon in summer and the mid-latitude westerlies in winter (Bookhagen and Burbank, 2010).

2.2 Glaciological mass balance measurements

The first series of measurements on Chhota Shigri Glacier started in 1987 (Nijampurkar and Rao, 1992; Dobhal et al., 1995; Kumar, 1999) but the MB measurements were abandoned after 1989. We reinitiated the mass-balance observations in 2002. Since that year, annual surface MB measurements have been carried out continuously on Chhota Shigri Glacier at the end of September or the beginning of October using the direct glaciological method (Cuffey and Paterson, 2010). Ablation was measured through a network of 22 stakes distributed between 4300 and 5000 m a.s.l., whereas in the accumulation area the net annual accumulation was obtained at six sites (by drilling cores or pits) between 5100 and 5550 m a.s.l. In the accumulation area, the number of sampled sites is limited due to difficulty of access and the high elevation. Details about direct MB measurements and calculations can be found in Wagnon et al. (2007) and Azam et al. (2012).

2.3 Geodetic mass balance from field measurements

Extensive glaciological field surveys were carried out between 1987 and 1989 in order to perform surface velocity, MB and gravimetric measurements (Dobhal, 1992; Dobhal et al., 1995; Nijampurkar and Rao, 1992; Kumar, 1999). For this purpose, 48 stakes were set up in the ice in 1987 and 84 in 1988. These stakes, along with 20 gravimetric stations were surveyed in 1988 by topographic measurements using a theodolite and a laser range finder. This resulted in 104 points on the glacier surface, whose position was known in 1988 with a horizontal/vertical accuracy of ±0.10 m (Dobhal, 1992) and covering 67 % of the surface area.

In October 2010, 91 of the 104 geodetic points originally measured in 1988 were surveyed again in the field using the carrier-phase global positioning system (GPS) to determine the thickness variations of the glacier over 22 yr. The other 13 points could not be measured due to access problems (crevasses). First, the old 1988 (Survey Of India, SOI) and the new 2010 (UTM) coordinate systems were homogenized thanks to 6 geodetic benchmarks engraved in 1988 in rocks around the glacier. GPS measurements performed on these benchmarks in 2010 allowed us to calculate the geometric transformation between the SOI and UTM coordinate systems. The residual error was less than 5 cm in horizontal and vertical components. From this transformation, the coordinates of the 104 points surveyed in 1988 were calculated in the UTM system. Second, we measured the elevations of the glacier surface at these points in order to obtain the thickness changes since 1988. Finally, these thickness changes are averaged by and applied to every 50 m altitude range area with data (67 % of the total area) and different thickness variations are tested for the unsurveyed glacier area (see Sect. 3.1 for details). Volume changes are converted into the total cumulative MB over the period 1988–2010, assuming that the mass loss is ice (density = 900 kg m^{-3}).

2.4 Geodetic mass balance from satellite stereo-imagery

Regional changes in ice elevation have been measured by differencing two DEMs generated from the 10–20 February 2000 Shuttle Radar Topographic Mission (SRTM; Rabus et al., 2003) and from Satellite Pour l'Observation de la Terre (SPOT 5) optical stereo imagery acquired 20 October 2011 (Korona et al., 2009). A complete description of the method used to adjust horizontally and vertically the DEMs and account for the C-band (SRTM) penetration into snow and ice can be found in Gardelle et al. (2012a, b). Volume changes are calculated by integrating elevation changes over the whole glaciarized area or over individual glaciers and converted to MB using a density of 900 kg m^{-3} for the volume-to-mass conversion. A seasonality correction, to cover 12 complete 12-month periods from October 1999 to October 2011, must be applied between mid October 1999 and mid February 2000, a 4-month period when glaciers are accumulating mass. Given the lack of measurement of winter MB in the Lahaul and Spiti region, our correction is based on a global mean winter MB of ca. 1 m w.e. assuming a 7-month duration of the accumulation season (typically from 15 September to 15 April of the following year). Thus we applied a correction of 0.15 m w.e. per winter month (Ohmura, 2011) and assigned a high uncertainty (100 %) to this correction.

3 Results

3.1 Changes in Chhota Shigri Glacier thickness and cumulative MB over the period 1988–2010

The thickness variations derived from the changes in elevation measured at each of the 91 points are plotted in Figs. 2 and 3. Except for the glacier tongue, we observe an overall uniform decrease in thickness changes with increasing altitude, ranging from ~ -8 m at 4500 m a.s.l. to -5 m at 5100 m a.s.l. (Figs. 2 and 3). Below 4500 m a.s.l., the thickness change differs from this trend. It could be due to the presence of debris cover which affects the sensitivity of ice ablation to solar radiation (Brock et al., 2000). Given that the debris cover comes from sporadic rock falls or lanslides and moves following the ice flow, the influence on thickness changes varies a lot with space as observed on other alpine glaciers (e.g. Berthier and Vincent, 2012). Between 4300 and 4500 m a.s.l., the debris cover is non-uniform and the thinning does not exceed -4 m (Fig. 2). The snout region between 4050 and 4300 m (1 % of the total glacier area), surrounded by very steep slopes and consequently heavily covered by debris, shows thickening that may be due to locally important snow or landslides (part of this snout region is an avalanche deposition area). Although the thickness changes are very heterogeneous in this region, it hardly affects the glacier-wide MB given that the surface area covered by debris is only 3.4 % of the total glacier area. Above 5100 m a.s.l. (33 % of the glacier area), no measurement of elevation change is available.

Below 5100 m a.s.l., the mean thinning is -5.6 m of ice, i.e. -5.0 m water equivalent (w.e.). The total volume change of the glacier was calculated using three different assumptions to capture the entire range of changes that could reasonably be expected for the unsurveyed area. First, thinning above 5100 m a.s.l. was assumed to be equal to that measured in the lower part, resulting in a cumulative MB of the glacier of -5.0 m w.e. between 1988 and 2010. Second, the upper part of the glacier was assumed to have experienced no elevation change since 1988, giving a cumulative MB of -3.3 m w.e. over the 22 yr. Third, the decreasing thinning trend observed between 4700 and 5100 m a.s.l. was extrapolated from the lower to the upper part, using a linear regression with altitude. This results in a cumulative MB of −3.8 m w.e. This third assumption seems to be the most reasonable given that, over a period of several decades, the elevation changes of non-surging glaciers generally approach zero toward the head of the glacier (Schwitter and Raymond, 1993).

A first source of error comes from the uncertainty associated with elevation changes in each altitude range. The standard deviation of measured elevation changes within each altitude range above 4500 m a.s.l. is never larger than 1 m w.e., and thus ±1 m w.e. is used as the uncertainty on elevation change for altitude ranges where measurements are available. In the unsurveyed upper part, where the thinning is assumed to be between 0 and −5 m w.e., this uncertainty is higher and assumed to be ±2.5 m. Weighting these uncertainties with the areas, the total uncertainty of the mean elevation change of the glacier is ± 1.5 m w.e. The area change between 1988 and 2010 which affects the calculation of the volume change can be neglected because the snout has retreated by only 155 m (Azam et al., 2012) in 22 yr corresponding to an insignificant surface area loss (< 0.1 % of the total surface area).

Another source of error comes from the choice of ice density to convert the volume change into MB. This is straightforward in the ablation zone where only ice is lost, but not so easy to estimate in the accumulation area where either firn or ice can be lost. As a sensitivity test, we also considered a density of 600 kg m^{-3} instead of 900 kg m^{-3} for the material lost above 4900 m a.s.l. The cumulative MB between 1988 and 2010 becomes −4.1, −3.0 and −3.3 m w.e. for asumptions 1 (same thinning above 5100 m a.s.l. as below), 2 (no thinning above 5100 m a.s.l.) and 3 (linear thinning) respectively. Consequently, the calculations with these two extreme-density scenarios shows that the maximum error due to unknown density is 1 m w.e. This error is summed quadratically with the error on elevation changes (1.5 m w.e.) to obtain a total error of 1.8 m w.e.

3.2 Representativeness of Chhota Shigri Glacier using spaceborne DEMs

We assess the representativeness of Chhota Shigri Glacier using remote sensing data by comparing its glacier-wide MB to the Lahaul and Spiti region-wide MB between 1999 and 2011. Figure 4 shows a complex regional pattern of elevation changes between 1999 and 2011 for a glaciarized area covering in total 2110 km^2. With -0.39 ± 0.15 m w.e. yr^{-1} (a cumulative 12-yr MB of -4.7 ± 1.8 m w.e.), the average glacier-wide MB for Chhota Shigri Glacier is not statistically different from the region-wide MB of -0.44 ± 0.09 m w.e. yr^{-1}. The 1999–2011 MB is less negative than the 1999–2004 MB reported previously (Berthier et al., 2007), both for Chhota Shigri Glacier and the Lahaul and Spiti region (Supplement). Note also that the values from Berthier et al. (2007) have been entirely recalculated to take into account a better understanding of the biases between DEMs (Supplement). Also in favor of the regional representativeness of Chhota Shigri Glacier, a good agreement was found between the glaciological and the regional ICESat-derived cumulative MB between fall 2003 and fall 2008 (Kääb et al., 2012, Supplement Fig. S6).

3.3 Mass gain of Chhota Shigri Glacier between 1988 and 1999

We combined the direct glaciological measurements (2010–2011) with the geodetic data using ground (1988–2010) and spaceborne data (1999–2011) to infer the 1988–1999 MB. The MB of Chhota Shigri Glacier measured in the field for the year 2010–2011 using the glaciological method was $+0.1 \pm 0.4$ m w.e. yr^{-1}, leading to a cumulative MB of -4.8 ± 2.3 m w.e. between 1999 and 2010. Given that the cumulative MB obtained from geodetic ground data was -3.8 m w.e. (Sect. 3.1) between 1988 and 2010, Chhota Shigri Glacier gained mass between 1988 and 1999 (cumulative MB of $+1.0 \pm 2.8$ m w.e.) before losing mass over the period 1999–2011 (cumulative MB of -4.7 ± 1.8 m w.e.).

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3.4 Comparison with other western Himalayan glaciers

Available field data from other glaciers in the western Himalaya have been compiled to obtain an up-to-date overview of their mass change over recent decades (Fig. 5). Several MB series in India started during the seventies but stopped during the eighties. The longest series reported over this period are those of Gara (9 yr; 1974–1983), Gor Garang (9 yr; 1976–1985) and Shaune Garang (9 yr; 1981–1990) glaciers, all located in the Baspa basin, Himachal Pradesh. Recent series longer than five years are those of Hamtah, Dokriani and Chhota Shigri glaciers. The Hamtah series started in 2000 but annual data after 2006 are not available. The Dokriani measurements started in 1991 and stopped in 2000, with a gap in 1995 and 1996, before starting again in 2007. Some of these glaciers are partially debris covered. From this compilation, despite the paucity of observations and large gaps in the series, MB averages are available over the last 4 decades in this region. In the same figure, the average MB of the Himalaya-Karakoram (HK) region has been plotted. These data come from the pentadal HK MB averages published by Cogley (2011) using the best up-to-date dataset.

4 Discussion

The MB series of Chhota Shigri Glacier measured since 2002 with the direct glaciological method has been extended back to 1988 using geodetic measurements. Over the whole period 1988–2010, the cumulative MB of Chhota Shigri Glacier was -3.8 ± 1.8 m w.e., corresponding to a moderate mass loss rate of -0.17 ± 0.08 m w.e. yr^{-1} in agreement with a snout retreat of only 155 m (a rate of 7 m yr^{-1}). In fact, this glacier experienced first a slightly positive cumulative MB between 1988 and 1999 followed by a period of ice wastage, confirming the presumption of Azam et al. (2012) that this glacier shifted from a state of near equilibrium to imbalance at the turn of the century. Using thickness measurements and surface ice velocities, Azam et al. (2012) calculated 2003/2004 ice fluxes which are far larger than the balance fluxes calculated from 2002–2010 average MB. They suggested that the glacier has experienced a period of near-zero or slightly positive MB in the 1990s, before shifting to a strong imbalance in the 21st century. This result is also supported by the ice velocities measured in 1987/1988 (Dobhal et al., 1995) which are very close to the 2003/2004 values suggesting that the dynamic behaviour of the glacier may not have changed much between 1988 and 2004. The observations available on other glaciers of western Himalaya are mostly limited to the period 1975–1990 revealing negative MBs except for some years (Fig. 5). The MB of Dokriani Glacier (Garhwal) was measured intermittently between 1991 and 2010 and does not allow us to obtain MB changes over the last two decades. Thus, this present study is filling a gap in the knowledge of western Himalaya glacier MB in the 1990s.

Given that during 1999–2011, the MB of Chhota Shigri Glacier is similar to the MB of a large glacier sample (covering over 2000 km^2) in the Lahaul and Spiti region, we suggest that this whole region may have been close to mass equilibrium during the nineties. This contrasts to our current knowledge of glacier MB in the HK region as reflected by recent compilations (Cogley, 2011; Bolch et al., 2012), that show negative values over the last four decades and an acceleration of glacier wastage after 1990. In fact, those HK MB averages over the last decades are questionable given the paucity of observations, especially in the 1990s. Moreover, due to a difficult access to the accumulation areas, it seems that some glaciers are probably surveyed only in their lower part (which is not always clearly mentioned in sources), making the glacier-wide MB biased negatively. This is probably the case of Dunagiri or Hamtah glaciers for which the MBs are strongly negative (Fig. 5) and, at least for Hamtah Glacier, are not consistent with our space-borne measurements. For this glacier, we measured a geodetic MB of -0.45 ± 0.16 m w.e. yr^{-1} during 1999–2011 whereas the glaciological MB was -1.46 m w.e. yr^{-1} during 2000–2009 (Table 1). Consequently, ground-based observational data used for the HK compilation are probably biased toward negative MBs.

Using remote sensing data, we showed that the MB of Chhota Shigri Glacier is similar to the region-wide MB in the Lahaul and Spiti region over the period 1999–2011. However, the western Himalaya is much larger than Lahaul and Spiti region and characterized by, from west to east, the decreasing influence of the mid-latitude westerlies and the increasing influence of the Indian monsoon (Bookhagen and Burbank, 2010), leading to distinct accumulation regimes on glaciers depending on their location. Given that the climatic sensitivity of glacier MB depends mainly on precipitation seasonality (Fujita, 2008), the response of these glaciers to climate change could be very different from one side to the other of western Himalaya and could explain part of the spatial and temporal variability observed in Fig. 5. Another cause of this heterogeneous pattern could be related to the debris cover of these glaciers. The Chhota Shigri Glacier is almost free of debris whereas some of the surveyed glaciers are partially debris covered. Thick debris cover reduces melting by shielding and insulating glacier surfaces (e.g. Kayastha et al., 2000). Many recent studies highlight the importance of debris cover in the contrasted glacier response to climate change (e.g. Fujita and Nuimura, 2011; Gardelle et al., 2012a; Kääb et al., 2012; Scherler et al., 2011). Given that thick debris cover is common in the Himalayas, it is very difficult to determine the sensitivity of the Himalayan glaciers to climate change. It results that the paucity and the sparsity of data do not allow us to give a consistent picture of the western Himalayan glaciers over the last 30 yr.

5 Conclusions

The Chhota Shigri Glacier gained mass in the 1990s before entering a period of mass loss since (at least) 1999, a behavior that is likely to be representative of other glaciers in the Lahaul and Spiti region. It reveals a peculiar evolution compared to the most recent compilations of MB data in the Himalayan range. The meteorological variables which caused these cumulative MB between 1988 and 1999 will be analyzed in a further study. As mentioned in numerous studies (e.g. Oerlemans, 2001) and especially for Himalayan glaciers with heavily debris-covered tongues (Bolch et al., 2012), length and area changes are poor indicators of climate change and are not very helpful to depict regional features of glacier changes. Although we filled a gap in our knowledge of the glacier MB for a region (Lahaul and Spiti) during the last two decades, we stress that these results cannot be applied to the whole Western Himalaya. Our results for the nineties support other recent findings that suggest a mass gain in the Karakoram and a spatially varying thinning in the Himalayas for the last decade (Gardelle et al., 2012a; Kääb et al., 2012). Altogether these studies contribute to draw a complex picture of Karakoram and Himalayan glacier response to recent climate change.

Consequently, and as now commonly accepted, there is an urgent need to maintain and develop long-term ground-based surface MB observations on benchmark glaciers in the Himalayas, covered or not by debris. Additionally, remote sensing techniques (based on aerial photographs or satellite images) must be used and improved to calibrate the cumulative MB of these glaciers, extend the observations to large areas and test the representativeness of glaciers monitored in the field. Geodetic MBs covering periods of 4 to 5 decades can also be inferred from satellite spy stereo-imagery acquired in the 60s and 70s (Bolch et al., 2011) and should, when possible, be extended to other regions of the Himalayas.

Supplementary material related to this article is available online at: http://www.the-cryosphere-discuss.net/6/3733/2012/tcd-6-3733-2012-supplement.pdf.

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References

Azam, M. F., Wagnon, P., Ramanathan, A., Vincent, C., Sharma, P., Arnaud, Y., Linda, A., Pottakkal, J., Chevallier, P., Singh, V. B., and Berthier, E.: From balance to imbalance: a shift in the dynamic behaviour of Chhota Shigri Glacier (Western Himalaya, India), J. Glaciol., 58, 315–324, doi:10.3189/2012JoG11J123, 2012.

Bajracharya, S. R. and Shrestha B.: The status of glaciers in the Hindu Kush-Himalayan region, Kathmandu, ICIMOD, 2011.

Berthier, E. and Vincent, C.: Relative contribution of surface mass balance and ice flux changes to the accelerated thinning of the Mer de Glace (Alps) over 1979–2008, J. Glaciol., 58, 501–512, 2012.

Berthier, E., Arnaud, Y., Kumar, R., Ahmad, S., Wagnon, P., and Chevallier, P.: Remote sensing estimates of glacier mass balances in the Himachal Pradesh (Western Himalaya, India), Remote Sens. Environ., 108, 327–338, doi:10.1016/j.rse.2006.11.017, 2007.

Bhambri, R., Bolch, T., Chaujar, R. K., and Kulshreshtha, S. C.: Glacier changes in the Garhwal Himalaya, India, from 1968 to 2006 based on remote sensing, J. Glaciol., 57, 543–556, 2011.

Bolch, T., Kulkarni, A., Kaab, A., Huggel, C., Paul, F., Cogley, J. G., Frey, H., Kargel, J. S., Fujita, K., Scheel, M., Bajracharya, S., and Stoffel, M.: The State and Fate of Himalayan Glaciers, Science, 336, 310–314, 2012.

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Bolch, T., Pieczonka, T., and Benn, D. I.: Multi-decadal mass loss of glaciers in the Everest area (Nepal Himalaya) derived from stereo imagery, The Cryosphere, 5, 349–358, doi:10.5194/tc-5-349-2011, 2011.
Bookhagen, B. and Burbank, D. W.: Toward a complete Himalayan hydrological budget: Spatiotemporal distribution of snowmelt and rainfall and their impact on river discharge, J. Geophys. Res., 115, F03019, doi:10.1029/2009JF001426, 2010.
Brock, B. W., Willis, I. C., and Sharp, M. J.: Measurements and parameterization of albedo variations at Haut Glacier d'Arolla, Switzerland, J. Glaciol., 46, 675–688, 2000.
Cogley, J. G.: Geodetic and direct mass-balance measurements: comparison and joint analysis, Ann. Glaciol., 50, 96–100, 2009.
Cogley, J. G.: Present and future states of Himalaya and Karakoram glaciers, Ann. Glaciol., 52, 69–73, 2011.
Cuffey, K. M. and Paterson, W. S. B.: The physics of glaciers, Fourth ed., Academic Press Inc., Amsterdam, 2010.
Dobhal, D. P.: Inventory of Himachal glaciers and glaciological studies of Chhota Shigri glacier, Himachal Pradesh: a case history, Ph.D. thesis of the Garhwal University, Srinagar, 1992.
Dobhal, D. P., Kumar, S., and Mundepi, A. K.: Morphology and glacier dynamics studies in monsoon-arid transition zone: an example from Chhota Shigri glacier, Himachal Himalaya, India, Current Sci., 68, 936–944, 1995.
Dobhal, D. P., Gergan, J. T., and Thayyen, R. J.: Mass balance studies of the Dokriani Glacier from 1992 to 2000, Garhwal Himalaya, India, Bull. Glaciol. Res., 25, 9–17, 2008.
Dyurgerov, M. B. and Meier, M. F.: Glaciers and the Changing Earth System: a 2004 Snapshot, INSTAAR, Boulder, 117 pp., 2005.
Fujita, K.: Effect of precipitation seasonality on climatic sensitivity of glacier mass balance, Earth and Planet. Sci. Lett., 276, 14–19, doi:10.1016/j.epsl.2008.08.028, 2008.
Fujita, K. and Nuimura, T.: Spatially heterogeneous wastage of Himalayan glaciers, P. Natl. Acad. Sci., 108, 14011–14014, 2011.
Gardelle, J., Berthier, E., and Arnaud, Y.: Slight mass gain of Karakorum glaciers in the early 21st century, Nature Geosci., 5, 322–325, doi:10.1038/ngeo1450, 2012a.
Gardelle, J., Berthier, E., and Arnaud, Y.: Impact of resolution and radar penetration on glacier elevation changes computed from multi-temporal DEMs, J. Glaciol., 58, 419–422, 2012b.

Gautam, C. K. and Mukherjee, B. P.: Mass-balance vis-à-vis snout position of Tipra bank glacier District Chamoli, Uttar Pradesh, Proc. Natl. Meet Himalayan Glaciol., 5–6 June 1989, 141–148, 1989.
Geological Survey of India (GSI): Glaciological studies on Dunagiri Glacier, district Chamoli (Field Seasons 1983-19-84 to 1991–1992), Final Report 1992, 5–9, 1992.
Geological Survey of India (GSI): Chapter 8, Annual Report 2010–2011, 69–70, 2011.
Immerzeel, W. W., van Beek, L. P. H., and Bierkens, M. F. P.: Climate Change Will Affect the Asian Water Towers, Science, 328, 1382–1385, 2010.
Kääb, A., Berthier, E., Nuth, C., Gardelle, J., and Arnaud, Y.: Contrasting patterns of early 21st century glacier mass change in the Himalaya, Nature, 488, 495–498, doi:10.1038/nature11324, 2012.
Kargel, J. S., Cogley, J. G., Leonard, G. J., Haritashya, U., and Byers, A.: Himalayan glaciers: The big picture is a montage, P. Natl. Acad. Sci., 108, 14709–14710, 2011.
Kaser, G., Großhauser, M., and Marzeion, B.: Contribution potential of glaciers to water availability in different climate regimes, P. Natl. Acad. Sci., 107, 20223–20227, doi:10.1073/pnas.1008162107, 2010.
Kayastha, R. B., Takeuchi, Y., Nakawo, M., and Ageta, Y.: Practical prediction of ice melting beneath various thickness of debris cover on Khumbu glacier, Nepal, using a positive degree-day factor, IAHS Publ., 264, 71–82, 2000.
Korona, J., Berthier, E., Bernard, M., Remy, F., and Thouvenot, E.: SPIRIT. SPOT 5 stereoscopic survey of Polar Ice: Reference Images and Topographies during the fourth International Polar Year (2007–2009), ISPRS J. Photogramm., 64, 204–212, doi:10.1016/j.isprsjprs.2008.10.005, 2009.
Koul, M. N. and Ganjoo, R. K.: 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, Climatic Change, 99, 119–139, doi:10.1007/s10584-009-9660-9, 2010.
Kumar, S.: Chhota Shigri Glacier: its kinematic effects over the valley environment, in the north-west Himalaya, Current Sci., 77, 594–598, 1999.
Nijampurkar, V. N. and Rao, D. K.: Accumulation and flow rates of ice on Chhota Shigri Glacier, central Himalaya, using radio-active and stable isotopes, J. Glaciol., 38, 43–50, 1992.
Nuimura, T., Fujita, K., Yamaguchi, S., and Sharma, R. R.: Elevation changes of glaciers revealed by multitemporal digital elevation models calibrated by GPS survey in the Khumbu

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region, Nepal Himalaya, 1992–2008, J. Glaciol., 58, 648–656, doi:10.3189/2012JoG11J061, 2012.
Oerlemans, J.: Glaciers and climate change, edited by: Oerlemans, J., A. A. Balkema Publishers, Rotterdam, 2001.
Ohmura, A.: Observed Mass Balance of Mountain Glaciers and Greenland Ice Sheet in the 20th Century and the Present Trends, Surveys in Geophysics, 32, 537–554, 2011.
Rabus, B., Eineder, M., Roth, A., and Bamler, R.: The shuttle radar topography mission – a new class of digital elevation models acquired by spaceborne radar, ISPRS J. Photogramm., 57, 241–262, 2003.
Raina, V. K.: Himalayan glaciers. A state-of-art review of glacial studies, glacial retreat and climate change. Ministry of Environment and Forests, India, available at: http://moef.nic.in/downloads/public-information/MoEF%20Discussion%20Paper%20_him.pdf, 2009.
Raina, V. K., Kaul, M. K., and Singh, S.: Mass-balance studies of Gara Glacier, J. Glaciol., 18, 415–423, 1977.
Scherler, D., Bookhagen, B., and Strecker, M. R.: Spatially variable response of Himalayan glaciers to climate change affected by debris cover, Nature Geosci., 4, 156–159, 2011.
Schwitter, M. P. and Raymond, C. F.: Changes in the Longitudinal Profiles of Glaciers during Advance and Retreat, J. Glaciol., 39, 582–590, 1993.
Shekhar, M. S., Chand, H., Kumar, S., Srinivasan, K., and Ganju, A.: Climate-change studies in the western Himalaya, Ann. Glaciol., 51, 105–112, 2010.
Shrivastava, D., Sangewar, C. V., Kaul, M. K., and Jamwal, K. S.: Mass balance of Rulung Glacier- a Trans-Himalayan glacier, Indus basin, Ladak. Proc. Symp. Snow, Ice and Glacier, March 1999, Geological Survey of India, Special Publication, 53, 41–46, 2001.
Thayyen, R. J. and Gergan, J. T.: Role of glaciers in watershed hydrology: a preliminary study of a "Himalayan catchment", The Cryosphere, 4, 115–128, doi:10.5194/tc-4-115-2010, 2010.
Wagnon, P., Linda, A., Arnaud, Y., Kumar, R., Sharma, P., Vincent, C., Pottakkal, J. G., Berthier, E., Ramanathan, A., Hasnain, S. I., and Chevallier, P.: Four years of mass balance on Chhota Shigri Glacier, Himachal Pradesh, India, a new benchmark glacier in the western Himalaya, J. Glaciol., 53, 603–611, 2007.
WGMS: Glacier Mass Balance Bulletin #11 (2008–2009), edited by: Zemp, M., Nussbaumer, S. U., Gärtner-Roer, I., Hoelzle, M., Paul, F., and Haeberli, W., ICSU(WDS)/IUGG(IACS)/UNEP/UNESCO/WMO, World Glacier Monitoring Service, Zurich, Switzerland, 20, 102 pp., 2011.

Table 1. Description of glaciers with glaciological MB series in the Western Himalaya.

Glacier number and name (Region/State)	Location	Area (km^2)	MB period	Mass balance ($m\,w.e.\,yr^{-1}$)	References
1. Neh Nar (Jhelum basin/ Jammu and Kashmir)	34°16′ N 75°52′ E	1.7	1975–1984	−0.53	Dyurgerov and Meier (2005)
2. Hamtah* (Lahaul-Spiti/ Himachal Pradesh)	32°24′ N 77°37′ E	3.2	2000–2009	−1.46*	GSI (2011)
3. Chhota Shigri (Lahaul-Spiti/ Himachal Pradesh)	32°20′ N 77°50′ E	15.7	2002–2010	−0.67	Wagnon et al. (2007) Azam et al. (2012)
4. Shaune Garang (Baspa basin/ Himachal Pradesh)	31°17′ N 78°20′ E	4.9	1981–1990	−0.23	Dyurgerov and Meier (2005)
5. Gara (Baspa basin/ Himachal Pradesh)	31°28′ N 78°25′ E	5.2	1974–1983	−0.27	Raina et al. (1977)
6. Naradu (Baspa basin/ Himachal Pradesh)	31°20′ N 78°27′ E	4.6	2000–2003	−0.40	Koul and Ganjoo (2010)
7. Gor-Garang (Baspa basin/ Himachal Pradesh)	31°37′ N 78°49′ E	2.0	1976–1985	−0.38	Dyurgerov and Meier (2005)
8. Tipra Bank (Garhwal Himalaya/ Uttarakhand)	30°44′ N 79°41′ E	7.0	1981–1988	−0.25	Dyurgerov and Meier (2005) Gautam and Mukherjee (1989)
9. Dokriani (Garhwal Himalaya/ Uttarakhand)	30°50′ N 78°50′ E	7.0	1992–1995 and 1997–2000	−0.32	Dobhal et al. (2008)
10. Dunagiri (Garhwal Himalaya/ Uttarakhand)	30°33′ N 79°54′ E	2.6	1984–1990	−1.04	GSI (1992)
11. Rulung (Zanskar range/ Jammu and Kashmir)	31°11′ N 78°08′ E	1.1	1980–1981	−0.11	Srivastava et al. (2001)
12. Shishram (Jhelum basin/ Jammu and Kashmir)	34°20′ N 75°43′ E	9.9	1983–1984	−0.29	Dyurgerov and Meier (2005)
13. Kolahoi (Jhelum basin/ Jammu and Kashmir)	34°20′ N 75°47′ E	11.9	1983–1984	−0.27	Dyurgerov and Meier (2005)

* −1.46 m w.e. is the mean MB over the period 2000–2009, but annual MBs are only available between 2000 and 2006, as reported in Fig. 5.

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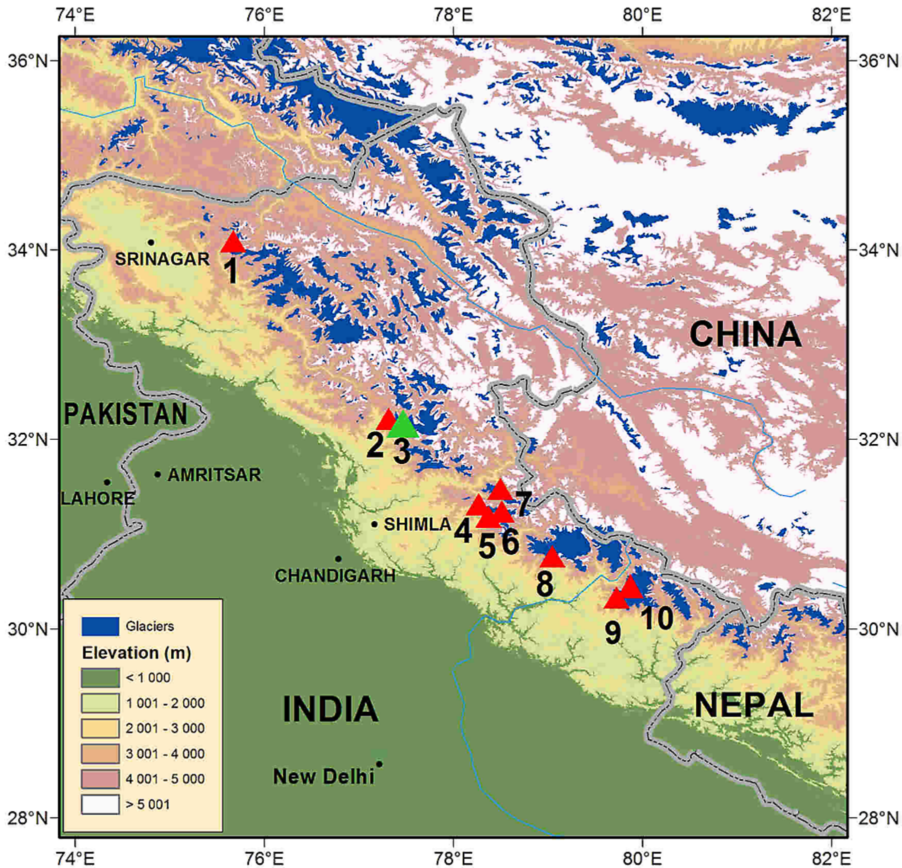

Fig. 1. Map of the western Himalayan glaciers with MB series longer than 1 yr. Details on each glacier (triangles) can be found in Table 1 with the corresponding numbers. Chhota Shigri Glacier has number 3 (green triangle).

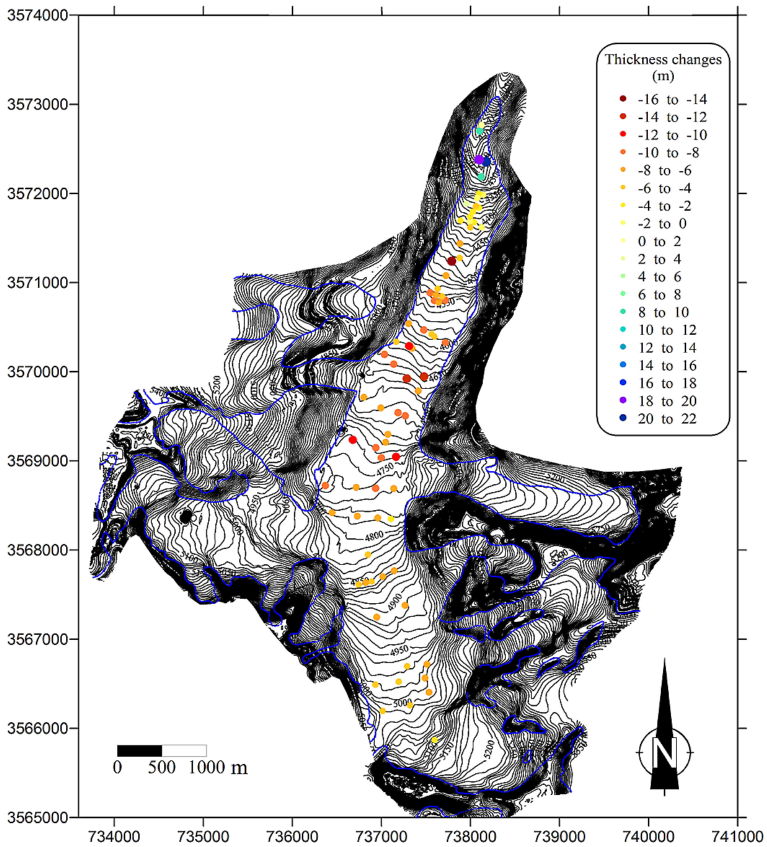

Fig. 2. Thickness changes of Chhota Shigri Glacier measured between 1988 and 2010, using geodetic measurements. The map coordinates are in the UTM43 (north) WGS84 reference system.

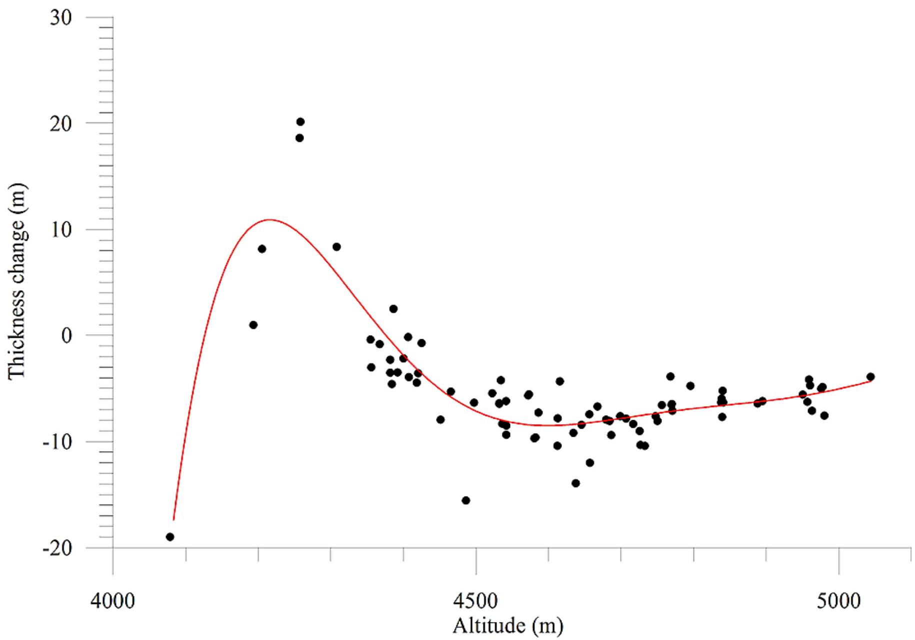

Fig. 3. Thickness changes as a function of altitude (measurements (black dots) and polynomial interpolation (red curve)).

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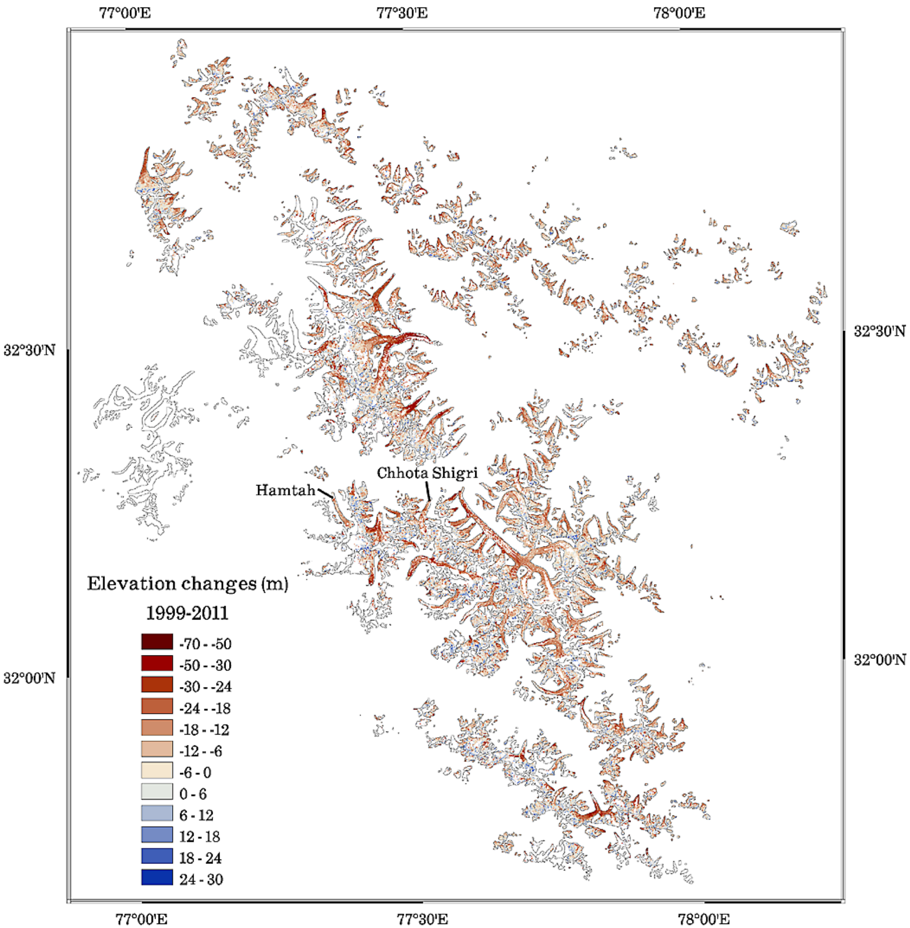

Fig. 4. Map of glacier elevation changes between 1999 and 2011, in Lahaul and Spiti region.

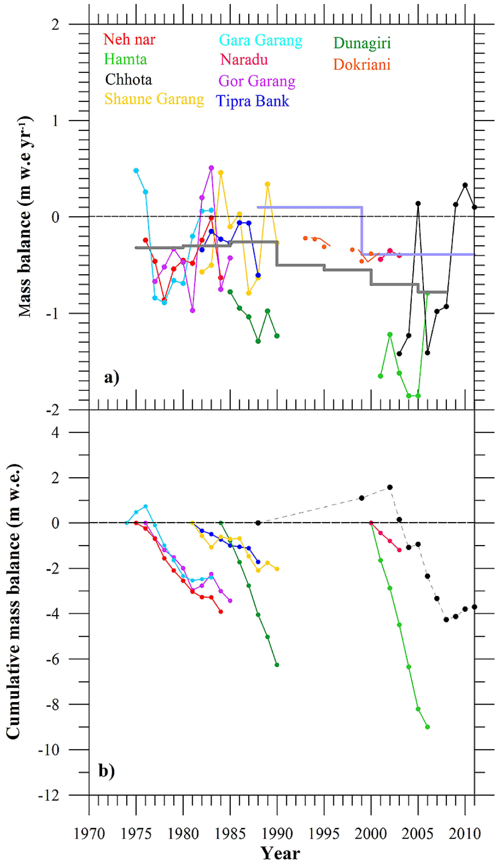

Fig. 5. MB of western Himalayan glaciers. **(a)** Annual glacier-wide MB of glaciers with more than one year of observations. The grey thick line corresponds to the pentadal Himalaya-Karakoram averages from Cogley (2011). The blue thick line comes from geodetic measurements of Chhota Shigri Glacier, **(b)** cumulative MBs.