Geodetic mass balance of Chhota Shigri Glacier and surrounding glaciers of the Lahaul/Spiti region. Revised estimates for 1999-2004 and new estimates for 1999-2011.

<u>Published and revised 1999-2004 mass balances</u>

In a previous publication (Berthier et al., 2007), we have compared the SRTM DEM (10-20 February 2000) and a SPOT5 DEM derived from 2.5 m resolution Spot5-HRG stereo-imagery (12 and 13 November 2004) to measure the region-wide mass balance of ca. 900 km² of glaciers (including Chhota Shigri Glacier) in the Lahaul/Spiti. Due to penetration into snow and ice of the radar signal, the SRTM DEM was assumed to represent the altitude of the glacier surface at the end of the 1999 melt season and thus the time stamp for the MB was 1999-2004. Various corrections were applied to the differential DEM, in particular a correction for an elevation-dependent bias estimated on the stable terrain and applied directly to the ice-covered areas. No formal error analysis was conducted in this 2007 paper but a range of values were reported assuming two density scenarios. For Chhota Shigri Glacier, we verified a reasonable consistency between the 1999-2004 satellite-derived and only two years (2002-2004) of glaciological MB available at that time (Wagnon et al., 2007).

Since 2007, some progress have been made to understand what was initially referred as an "elevation bias" in the SRTM DEM (Berthier et al., 2006). Paul (2008) attributed this bias to the difference in resolution of the DEMs and suggested that no correction of the differential DEM was needed. Building upon those findings, Gardelle et al. (2012a) recommended a correction of this "resolution bias" using a relationship between elevation difference and maximum curvature. The latter authors also proposed a correction of the radar penetration into snow/ice using the differentiation of two DEMs acquired simultaneously during the SRTM mission in X and C Bands. Given these improved corrections, we believe it is worth presenting here some revised values for the 1999-2004 geodetic MB together with their uncertainties calculated as proposed in (Gardelle et al., 2012b).

The comparison of the published and revised 1999-2004 MB for Chhota Shigri Glacier (Table A1) indicates only a small difference, less than 0.1 m w.e. yr^{-1}. However, due to the small size of the glacier (15.7 km²) and the short time separation (5 years), the error bar for the revised MB is large at ± 0.44 m w.e. yr^{-1}. Thus, we cannot rule out that this agreement between the published and revised values is partly coincidental. At -0.65 ± 0.17 m w.e. yr^{-1}, the regional (868 km² of glaciers) MB is now slightly less negative than published in the 2007 paper. Nevertheless, the statement that glaciers in the Lahaul/Spiti lost mass rapidly between 1999 and 2004 remains unchallenged.

Table A1: Comparison of the 1999-2004 geodetic MB (m w.e. yr^{-1}) published previously (Berthier et al., 2007) and the revised values using up-to-date corrections and errors analysis. In the 2007 publication, no error analysis was performed but two values were provided corresponding to two density scenarios for the volume-to-mass conversion in the accumulation area.

	Chhota Shigri[A]	Whole region[B]
Area (km²)	15.7	867.9
MB RSE-2007	-1.12 / -1.02	-0.85 / -0.69
MB This study	-1.03 ± 0.44	-0.65 ± 0.17

[A]: the Chhota Shigri area was 16.5 km² in (Berthier et al., 2007) but revised to 15.7 km² in (Wagnon et al., 2007) based on new glacier outlines drawn on high resolution imagery and verified using field observations.

[B]: the total ice-covered inventoried was 915.5 km² in (Berthier et al., 2007) but only 868 km² were actually covered with the 2004 Spot5-HRG DEM.

<u>Comparison of mass balances for 1999-2004, 2004-2011 and 1999-2011</u>

Recently, a new DEM of the Spiti/Lahaul area has been derived from Spot5-HRS imagery (Korona et al., 2009) acquired 20 October 2011. The longer time separation (12 yr instead of 5 yr) with the SRTM DEM implies reduced errors on the annual MB. Another advantage of this recent DEM compared to the 2004 DEM is that it is derived from a sensor, Spot5-HRS, which acquires stereo-imagery along track (Bouillon et al., 2006). The two images of the stereo-pair share the same orbital parameters and thus, one can expect less distortions in the DEM. This new DEM and our updated DEM adjustment method (Gardelle et al., 2012a) are used to calculate the 1999-2011 MB. In the sake of completeness, the SPOT5-HRG 2004 and SPOT5-HRS 2011 DEMs are also compared without the need for any correction of the penetration into snow and ice because both DEMs are derived from optical imagery.

In Table A2, we compare the geodetic MB for 1999-2004 (period I, MB^{I}), 2004-2011 (period II, MB^{II}), and 1999-2011 (period III, MB^{III}). Ideally, the time-weighted sum of MB^{I} and MB^{II} should equal MB^{III}. The difference between MB^{I+II} and MB^{III} reaches 0.36 m w.e. yr^{-1} for Chhota Shigri Glacier which highlights the challenge of computing the MB of relatively small glaciers from coarse DEMs (90 m for the SRTM DEM, 40 m for the SPOT5 DEMs) acquired only a few years apart and the importance of averaging over large regions. Indeed, the difference between MB^{I+II} and MB^{III} is only 0.08 m w.e. yr^{-1} for 868 km² of glaciers in the Lahaul and Spiti region.

Table A2 : Geodetic MB (m w.e. yr^{-1}) during 1999-2004, 2004-2011 and 1999-2011. All values in this tables are calculated using the corrections and errors analysis proposed by (Gardelle et al., 2012b, a). For each time interval, all valid DEM pixels are used contrary to Table A3 below, in which only pixels which are valid in all three DEMs are used.

MB	Chhota Shigri	Whole region
Area (km²)	15.7	867.9
MB^{I}: 1999-2004	-1.03 ± 0.44	-0.65 ± 0.17
MB^{II}: 2004-2011	-0.55 ± 0.42	- 0.42± 0.05
MB^{I+II}: $(5*MB^{I}+7*MB^{II})/12$	- 0.75 ± 0.31	- 0.52± 0.08
MB^{III}: 1999-2011	-0.39 ± 0.15	-0.44 ± 0.09

Part of the differences between MB^{I+II} and MB^{III} in Table A2 may however be explained by a varying sampling of the glaciers during the different time intervals due to clouds, shadows or lack of image texture in the accumulation areas. For example, the lower reaches of Chhota Shigri Glacier were poorly mapped by the November 2004 SPOT5 DEM due to important shadows at this time of year from the surrounding steep slopes. This affects MB^{I} and MB^{II} but not MB^{III}. Similarly, there are clouds in part of the 2011 DEM, which affects the 'whole region' estimates MB^{II} and MB^{III} but not MB^{I}. For this reason, we also provided in Table A3 the MB for the three different periods when exactly the same spatial sampling is applied to all glaciers, i.e., always neglecting pixels that are unreliable in at least one of the DEM. For Chhota Shigri, in this case, less than one third of the glacier area contains valid pixels and this third is not representative of the glacier hypsometry (Figure A1). After this homogenization, the difference between MB^{I+II} and MB^{III} for Chhota Shigri Glacier is reduced from 0.36 m w.e. yr^{-1} to 0.16 m w.e. yr^{-1} (Table A2 and A3). When the whole region is considered (868 km² of glaciers of which 409 km² are covered by valid pixels in all three DEMs), this difference, initially at 0.08 m/yr w.e., is reduced to only 0.01 m/yr w.e.

Table A3: Same as Table A2 but using only pixels which are valid in all three DEMs to avoid the sampling issues described in the text.

MB	Chhota Shigri	Whole region
Area (km²)	15.7	867.9
Area with valid pixels (km²)	5.1	408.7
MB^{I}: 1999-2004	- 1.09 ± 0.53	- 0.71± 0.18
MB^{II}: 2004-2011	- 0.28 ± 0.47	- 0.34± 0.05
MB^{I+II}: $(5*MB^{I}+7*MB^{II})/12$	-0.62 ± 0.35	-0.49 ± 0.08
MB^{III}: 1999-2011	- 0.46 ± 0.19	- 0.48 ± 0.08

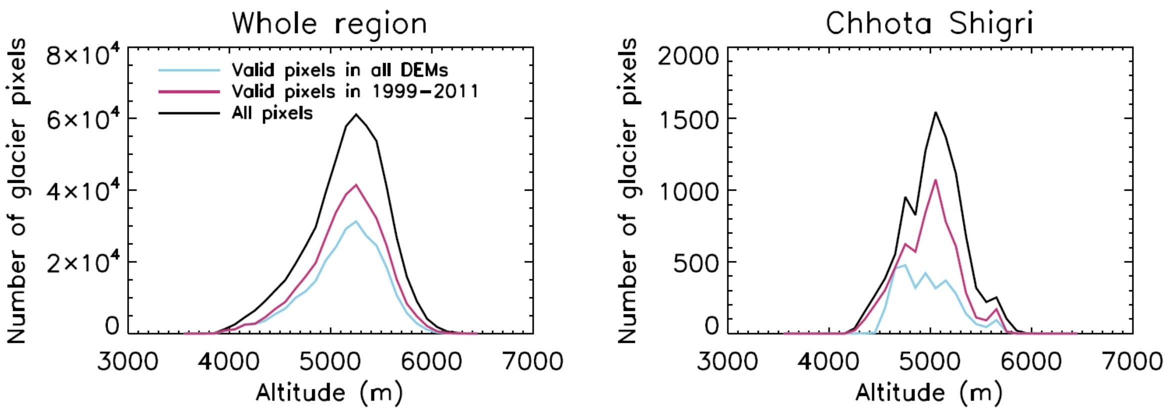

Figure A1: Hypsometry of the ice-covered area of the whole region (left, 868 km² in total) and Chhota Shigri Glacier (right, 15.7 km²) and its sampling by the differential DEMs. The black curve corresponds to all pixels, the red curve to DEM pixels which are valid in the 1999-2011 differential DEM and the blue curve to the pixels which are valid in all differential DEMs. Those distributions show that the whole region is well-sampled in both cases whereas for Chhota Shigri Glacier, the 1999-2011 sampling is adequate but not the sampling by valid pixels in all three DEMs.

These observations confirm the excellent relative adjustment of the DEMs when the complete scene is considered but also that local elevation biases remain, leading to error on MB for individual glaciers (here Chhota Shigri). This is not surprising given that our method of space-borne DEM adjustment aims at minimizing the elevation difference for the whole ice-free terrain present in the satellite scenes. Locally, some elevation differences may persist due to un- or difficultly- modelled short scale errors in the DEMs (Nuth and Kääb, 2011;Berthier et al., 2007;Berthier et al., 2012). These local elevation biases lead to errors in the MB for individual glaciers but average out when the whole glaciarized area, spread in the whole satellite scene as the stable terrain, is considered. Those local biases may partly explain the discrepancies in the early 21st century mass balances of individual glaciers in the Everest area between Bolch et al. (2011) and Nuimura et al. (2012, Table 2).

Based on this analysis, we conclude that:

(1) Care must be taken before computing the geodetic MB for a single glacier covering a few km^2 or tenth km^2, especially when the space-borne sensors used to compute the DEMs have a short time separation, different resolutions and work in different wavelength of the electromagnetic spectrum (radar vs. optical data). In such cases, a local adjustment of the DEMs using only the stable terrain within a short distance of the glacier of interest may be preferable (Miller et al., 2009).

(2) The 1999-2011 assessment (MB^{III}) is the one for which the sampling of Chhota Shigri is best (Figure A1, right) and, for which the error bars are smallest due to the longest time separation. To reconstruct the MB of Chhota Shigri Glacier between 1988-1999 (main text), it is thus preferable to use this 12-year estimate (1999-2011) and one year of field mass balance (2010-2011) than the 1999-2004 geodetic estimates combined with the cumulative field mass balance between 2004 and 2011.

(3) Importantly, these 12-yr geodetic estimates suggest that the MB of Chhota Shigri Glacier is representative of the regional glacier MB in the Lahaul/Spiti.

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