**Clarification concerning Chhota Shigri annual mass balance** by Patrick WAGNON (IRD, LGGE/LTHE, Grenoble, France) and Alagappan RAMANATHAN (School of Environmental Sciences, Jawaharlal Nehru University, New Delhi, India)

In the anonymous short comment posted on March 7th, point #3 discusses the reliability of Chhota Shigri Glacier annual mass balance data saying that there are "serious biases in mass balance observations (2002-10)". As pointed out by the authors of this short comment (referred to as $ASC_{7March}$ therein) in their point #1, we agree that field-based mass balance series should be systematically validated and, if necessary calibrated, from time to time (typically 10 years) using geodetic methods because mass balance observations using the glaciological method can be systematically biased (Zemp et al., 2013). However, in $ASC_{7March}$ comment #3, there are some issues that need to be clarified:

- In 2005-06, $ASC_{7march}$ are saying that there is no accumulation measurement, and only one single accumulation measurement in 2006-07 as well as in 2007-08, making the observed negative glacier-wide mass balance of these specified years questionable. Actually, we have performed point mass balance measurements systematically up to 5200 m asl every year, and when possible, up to 5500 m asl. Unfortunately, as explained in Wagnon et al. (2007) (section 4. Methodology), performing measurements up to 5500 m was not always possible due to difficult (deep snow) and sometimes dangerous (avalanches, crevasses) access. One site initially chosen at 5400 m asl has been abandoned (as also specified in Wagnon et al (2007)) because it was exposed to avalanches. Nevertheless, over the period 2002-10 (8 years), we could still perform accumulation measurements up to 5500 m asl during 4 years (2002-03, 2003-04, 2004-05, and 2008-09). Table 1 below gives the list of point mass balance measurements that have been performed above 5100 m asl every year, between 2002 and 2010.

Table 1: point mass balance measurements performed above 5100 m asl between 2002 and 2010, with their respective elevations

| | 2002-03 | 2003-04 | 2004-05 | 2005-06 | 2006-07 | 2007-08 | 2008-09 | 2009-10 |
|---|---|---|---|---|---|---|---|---|
| Number | 3 | 3 | 3 | 1 | 2 | 2 | 6 | 5 |
| Elevations (m a.s.l.) | 5180A / 5400A / 5500A | 5180A / 5400A / 5500A | 5180A / 5500A/ 5200B | 5180A | 5180A / 5200B | 5180A / 5200B | 5160A / 5180A / 5180A / 5500A / 5200B / 5300B | 5160A / 5180A / 5180A / 5200B / 5300B |

A and B refer to the parts A and B of Chhota Shigri Glacier, respectively (see fig 1, Wagnon et al., 2007)

We would like to stress that these point mass balance measurements performed in the accumulation area are among the most reliable measurements that we can expect in the Himalayas. Indeed, an artificial colored reference layer localizable using a Recco tablet has systematically been recognized while drilling the following year (see Wagnon et al, 2007 and 2013; Methodology sections for details). For Himalayan glaciers, the measurement technique with artificial reference levels is necessary to perform reliable accumulation measurements. Moreover, all the selected sites (except the site at 5400 m) are rather flat areas, where there is no avalanche activity. After 2008, we visited more accumulation sites to assess the spatial

variability and the representativeness of the initial sites selected in 2002 (list in Table 1). It turned out that the initial sites are very relevant to assess the accumulation on both parts A and B of the glacier (see Fig 1; Wagnon et al, 2007). In 2005-06, the site surveyed at 5180 m asl (part A) was in ablation, so it is true that there was no accumulation measurements. In 2006-07, and 2007-08, only the measurements performed at 5180 m on the part A gave accumulation, the point at 5200 m on the B part was in ablation. But for the years without measurement at 5500 m, we systematically extrapolated the measurements at 5100-5200 m asl to higher elevation using a mean gradient of mass balance as a function of elevation, calculated with the 4 other years with data. The methodology was perhaps not well described in Wagnon et al (2007) but it is the same as that applied on Mera Glacier, Nepal (Wagnon et al., 2013). Consequently, we do believe that the negative glacier-wide mass balances obtained for 2005-06, 2006-07 and 2007-08 are reliable.

- $ASC_{7march}$ comment a figure published by Ramanathan (2011) in an internal report for the Department of Science and Technology, Ministry of Science and Technology, India (http://www.serb.gov.in/pdfs/Publications/Chhota-Shigrii.pdf). In figure 2.7 of the report, $ASC_{7march}$ are surprised to see a large variability of point mass balance measurements at 4800-4900 m asl in 2009-10, and therefore question the reliability of the positive mass balance (+0.33 m w.e.), because they suppose that this large variability is due to avalanche-exposed site. Actually, this Figure 2.7 was a working document published in an internal report, which was also reviewed by Dr. C. V. Sangewar (Ex-Director, Glaciology Division, Geological Survey of India), Dr. D.R. Sikka (Ex-Director, Indian Institute of Tropical Meteorology), Dr. R. K. Midha (Ex-Advisor, Department of Science and Technology) and Dr. Rasik Ravindra (Director, National Centre for Antarctic and Oceanic Research and Chairman, Expert Committee on Dynamics of Himalayan Glaciers) before being published by Department of Science and Technology, Govt. of India. The positive point mass balances reported in this Figure 2.7 at 4800-4900 m asl for the year 2009-2010 were based on preliminary field observations (including some wrong stake readings) and has been corrected later to assess the glacier-wide mass balance. The correct figure is provided below (showing point mass balance field measurements as well as extrapolated accumulation data at 5500 m asl when they were missing i.e. in 2005-06, 2006-07, 2007-08 and 2009-10).

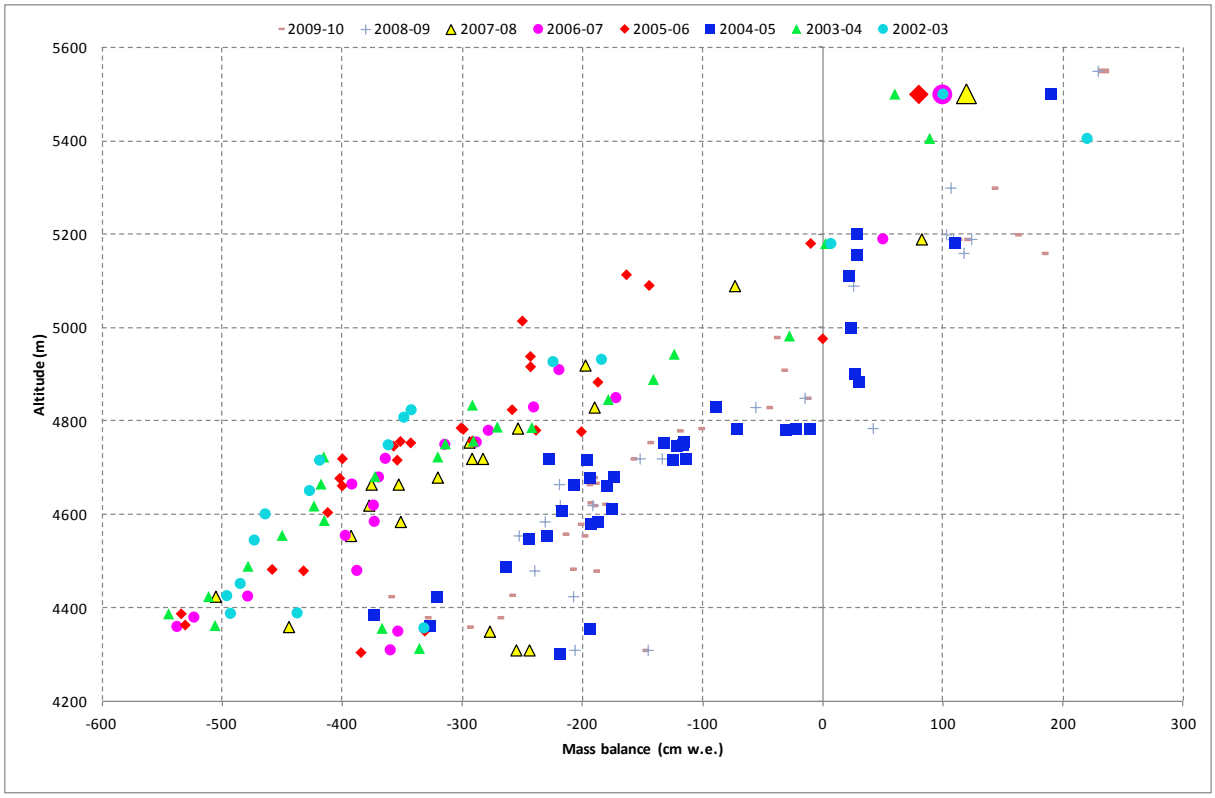


Figure : Annual point mass balance vs altitude, on Chhota Shigri Glacier, for 8 hydrological years (Symbols with bigger size at 5500 m asl refer to extrapolated values in 2005-06, 2006-07, 2007-08 and 2009-10)

This update figure provides all direct measurements (or extrapolated values at 5500 m) that have been used to derive the annual glacier-wide mass balance of Chhota Shigri Glacier between 2002 and 2010. This is an update version of the figure 3 (Wagnon et al, 2007) so we disagree when the $SC_{7March}$ authors suggest that we did not want to provide such information to the scientific community. But we believe that such information is lacking for Hamtah Glacier to allow the scientific community to examine the methodology followed and the field observation data that were used to generate the glacier wide annual mass balance (as stresses in $ACS_{7march}$ point #2). As pointed out by $ASC_{7march}$, there are still areas where the spatial variability is large, mainly above 5100 m asl. Indeed, at these elevations, slopes have various aspects (see the specific discussion 5.2 addressing this point in Wagnon et al, 2007). Consequently, this large variability observed above 5100 m asl is mainly due to aspect, may be also partly due to wind redistribution (although it is probably marginal since winds are not very strong) but not due to avalanches. Still there are some places where Chhota Shigri Glacier experiences avalanche activities (as said in Wagnon et al, 2007) but applying an area-weighted average to all these measurements indirectly should take into account this effect.

As a conclusion, we can say that the glaciological mass balance observations performed on Chhota Shigri Glacier are reliable, but can be biased like any other field-based mass balance series. As written in Wagnon et al (2007) “the accuracy of *b*n cannot be strictly evaluated, but is approximately ±20cm w.e., a typical error range for mass balance data (e.g. Jansson, 1999). Year-to-year relative differences are still instructive because annual values refer to the same map, to the same area–

elevation distribution function and to the same measurement network". To be even more cautious, this accuracy has been revised to ±0.4 m w.e. in Azam et al (2012).

To assess any potential bias, we compared these observations to geodetic mass balance observed from space in Vincent et al (2013) and, although the period does not match totally, both methods are in agreement. We still need to perform geodetic mass balance validation over identical periods that we are planning to do in the future using a new DEM from Pléaides stereo-imagery (to be acquired) that will be compared to the SPOT5 DEM from autumn 2004.

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 , India), J.Glaciol., 58, 315–324, doi:10.3189/2012JoG11J123, 2012.

Jansson, P. 1999. Effect of uncertainties in measured variables on the calculated mass balance of Storglacia¨ren. *Geogr. Ann.,* **81A**(4), 633–642.

Ramanathan, A. L.: Status Report on Chhota Shigri Glacier (Himachal Pradesh), Himalayan Glaciology Technical Report No. 1, Department of Science and Technology, Ministry of Science and Technology, New Delhi, 88 pp., 2011. 645. http://www.serb.gov.in/pdfs/Publications/Chhota-Shigrii.pdf

Vincent, C., Ramanathan, Al., Wagnon, P., Dobhal, D.P., Linda, A., Berthier, E., Sharma, P., Arnaud, Y., Azam, M. F., Jose, P.G., and Gardelle, J.: Balanced conditions or slight mass gain of glaciers in the Lahaul and Spiti region (Northern India, Himalaya) during the nineties preceded glacier shrinkage, The Cryosphere*,* 7, 1-14, doi: 10.5194/tc-7-1-2013, 2013

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.

Wagnon, P., C. Vincent, Y. Arnaud, E. Berthier, E. Vuillermoz, S. Gruber, M. Ménégoz, A. Gilbert, M. Dumont, J. Shea, D. Stumm & B. K. Pokhrel, Seasonal and annual mass balances of Mera and Pokalde glaciers (Nepal Himalaya) since 2007, *The Cryosphere,* 7, 1769-1786, doi:10.5194/tc-7-1769-2013, 2013

Zemp, M., Thibert, E., Huss, M., Stumm, D., Rolstad Denby, C., Nuth, C., Nussbaumer, S. U., Moholdt, G., Mercer, A., Mayer, C., Joerg, P. C., Jansson, P., Hynek, B., Fischer, A., Escher-Vetter, H., Elvehøy, H., and Andreassen, L. M.: Reanalysing glacier mass balance measurement series. The Cryosphere, 7, 1227-1245, doi:10.5194/tc-7-1227-2013, 2013.