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The Cryosphere Discussions

Interactive comment on "Mass gain of glaciers in Lahaul and Spiti region (North India) during the nineties revealed by in-situ and satellite geodetic measurements" *by* C. Vincent et al.

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Response to Referee #1

CS = Chhota Shigri

General comments

1. In this paper, authors addressed to evaluate mass balance of Chhota Sigri Glacier for recent 22 years by in-situ measurements and updated remote sensing based procedure (based on method of Gardelle et al. 2012a,b). The result mass gain of glaciers in 1990s is very impressive and interesting finding. However, I consider the assertion

should weaken because mass balance error in 1990s (± 2.5 m w.e.) is too large comparison with change itself (+ 1.0 m w.e.). Stable or balanced condition might be better than "mass gain".

We agree with referee's comments when saying that the assertion "Mass gain" in the title and in the text should be weakened given that the slightly positive mass balance is statistically not different from 0. The word "Mass gain" in the title has been changed to "Balanced or slightly positive mass budget" and the assertions corresponding to "Mass gain" have been weakened all along the text. We also restricted the title to CS Glacier, and the validity of this statement for the rest of the region is now presented as an hypothesis and discuss more thoroughly (a full paragraph is dedicated to this in the discussion).

2. The main result of this paper are not so different with the story of Azam et al. (2012). And some main assertions (mass gain in 1990s, representativeness of Chhota Sigri Glacier in analyzed region) lack rational evidence. So, I consider this manuscript has not reached to publish level yet.

We do not agree with referee #1 while saying that the main result of our paper is not so different from Azam and others (2012). Contrary to Azam and others, here, we bring a unique quantification based on accurate field data of the cumulative mass balance of CS Glacier between 1988 and 2010. It has never been done before. Azam and others could just infer qualitatively and indirectly a steady state of the glacier before 2002, based on a dynamical approach. In this mountain range of the world, where data are especially scarce and difficult to obtain, and where there is a specific gap of mass balance data in the nineties (as underlined by reviewer#2, T. Bolch), this dataset is valuable, and this paper does bring a new contribution to our knowledge of long-term (still only 22 years, but in this area, it can be considered as long-term) mass balance of an index glacier. This specific and new contribution of this paper (compared to Azam and others) is now clearly specified in discussion. We understand that the first version of this paper was not clear enough to present this finding, and we are hoping that the revised version was improved. Concerning the representativeness of CS in analyzed region, see the reply to comment 4 by Rev#2 . We revised thoroughly the manuscript and brought new evidence.

Specific comments

3. 3739/24 : The two assumptions of extreme cases and one assumption of intermediate case are adequate for evaluating mass balance and maximum error. However, area of tributaries look like large in the glacier. Is same extrapolation method applicable to tributaries? You can check spatial distribution from remote sensing derived result.

We have compared the elevation changes for the tributaries and the main trunk of CS Glacier (see Figure below). We stress that those mean elevation differences are computed using a limited number of pixels (typically $\sim$50) and need to be interpreted cautiously. Within each 50-m altitude interval, the elevation difference for the tributaries and the main trunk are never statistically different, at the 1-sigma level.

For the altitude range [4700 m:5100 m] which is common to the main trunk and the tributaries and where geodetic field measurement are available during 1988-2010, averaging all valid measurements leads to mean elevation differences of: -9.2 $\pm$ 1.5 m for the tributaries (area with valid measurements 2.0 km^2) -8.9 $\pm$ 1.3 m for the main trunk (area with valid measurements 2.8 km^2)

See Figure below: Elevation changes (dh) of CS Glacier between 1999 and 2011 for the main trunk (blue triangles) and the tributaries (red dots). The cumulative hypsometry (%) is shown as a blue dashed line (main trunk) and a red dashed line (tributaries). Error bars on dh were calculated using the number of valid measurements of dh in each 50-m altitude interval and taking into account a correlation length of 500 m ($\sim$12 pixels).

This figure is not included in the revised paper but we added the following sentence in the text: "Our 1988-2010 geodetic field measurements are restricted to the main trunk

of CS Glacier and did not sample the tributaries. To verify that no bias was induced by this incomplete sampling, we averaged the 1999-2011 remotely-sensed elevation changes of the tributaries and the main trunk between 4700 m a.s.l., the lower limit of the tributaries, and 5100 m a.s.l, the uppermost altitude of the 1988-2010 geodetic field measurements. At -9.2 $\pm$ 1.5 m for the tributaries (area with valid measurements: 2.0 km^2) and -8.9 $\pm$ 1.3 m for the main trunk (area with valid measurements: 2.8 km^2), the mean elevation changes are very similar and not statically different at the 1-sigma level. This observation justifies our assumption that measurements on the main trunk are representative of the rest of CS Glacier below 5100 m a.s.l."

4. 3743/3 : The velocities value in 1987/1988 and 2003/2004 should be shown here. Additionally, if you discuss about dynamic behavior, fluxes should also be shown here.

Here, we referred to the results of Azam and others (2012) in order to show that the presumption of this study is confirmed by our present study. The velocities and fluxes data have been published in Azam and others (2012) and we believe that it is not necessary to show them again since our present study does not deal with the dynamic behaviour of the glacier. Anyway, these sentences were confusing and have been replaced by two new sentences explaining in which way our present study is different from and complementary to Azam and others.

5. 3740/7 : Considering $\pm$ 1 m w.e. as uncertainty of all altitude range is too simplistic. You should examine altitudinal trend of uncertainty. Showing average and standard deviation of each altitude range in Fig.3 might be better as point with error bar.

Agree. The uncertainties have been revised. Figure 3 has been changed. Standard deviations are shown in Figure 3. See the Figure below

6. 3741/2 : Resolution size should be shown. It is basic information for remote sensing study. I recommend to include subset closeup image of Chhota Sigri Glacier in Fig.4.

Agree. See the Figure below. A Table was added:

Table 1: Characteristics of the remotely-sensed DEMs used in this study.

Sensor Date Coverage Posting (m) Method Reference SRTM ∼10-20 Feb. 2000 quasi-global (56S to 60N) 90 m SAR interferometry Rabus et al. 2003 SPOT5-HRG 12-13 Nov. 2004 868 km^2 of glaciers 90 m Across-track stereo-imagery Berthier et al. 2007 SPOT5-HRS 20 Oct. 2011 2110 km^2 of glaciers 40 m Along-track stereo-imagery Korona et al. 2009

7. 3740/17 : Strictly, error estimation should be done considering altitude. Quadratical error summation above 5100, between 4900 and 5100, and lower 4900 m a.s.l. are 2.7 (error of elevation change: 2.5, error of density: 1), 1.8 (err. of elev. :1.5, err. Of density: 1), and 1.5 (err. of elev. :1.5, err. of density: 0) respectively.

Agree. The uncertainties have been revised.

8. 3743/18 : Inconsistency between your space-borne measurements and previous glaciological measurements should be explained more rationally. The phrase Probably biased lacks evidence here. If you assume previous surveys were only carried out in their lower accessible part. You should compare between your space-borne measurements in lower part and previous result. Anyway spatial distribution of elevation change in Fig.4 should be examined more.

We have now added a close-up view of the elevation changes including CS and Hamtah glaciers (Fig. 5 of the revised manuscript and Figure below). However we disagree with reviewer#1 that in the case of Hamtah Glacier this map could allow verifying whether field measurements were restricted to the lower accessible part. This is due to the fundamental difference between local mass balance (measured in the field, not influenced by glacier flow) and elevation changes which are the combination of local mass balance and glacier flow (e.g., emergent velocities, see textbooks or a recent paper by Nuth et al. JOG vol 58, p119–133, 2012). In other words, the mean of all glaciological mass balance measurements in the ablation area will always be (much) more negative than the mean elevation changes and thus comparing the two would not

be conclusive. Only the glacier-wide mass balance from the two methods can be compared safely. In the last paragraph of section 4.1, we discuss the discrepancy between field measurements and space-borne measurements for Hamtah Glacier.

9. 3744/10 : How much area of glaciers covered by debris in the region? If there are so much debris-covered glacier in the region. Considering Chhota Shigri Glacier as representative glacier in the region would include negative bias. Actually MB of Chhota Shigri Glacier is negatively larger than regional MB.

The percentage of debris cover for the whole region (13%) was added. The CS Glacier, with debris covering only 3.4%, could be more sensitive. Indeed, as mentioned by reviewer#1, it could lead to a negative biais (i.e with mass balance more negative than for other glaciers).. However, several recent studies, mentionned below, show that the observed thinning rates of glaciers with or without debris cover are not significantly different .

Gardelle J., Berthier E., and Arnaud Y. Slight mass gain of Karakorum glaciers in the early 21st century, Nature Geoscience, 5, 322-325, 10.1038/ngeo1450, 2012. "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."

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, 10.1038/nature11324, 2012. "For the entire HKKH, our elevation trends on clean and debris-covered ice show no significant difference (Table 1). To avoid bias related to differences in the geographic and topographic distributions between clean and debris-covered ice, this comparison is based upon pairs of footprints sharing similar location, elevation, slope and aspect"

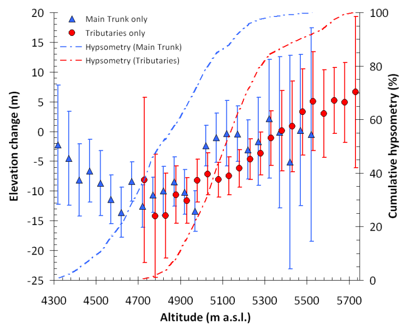
Nuimura T., Fujita K., Yamaguchi S., and Sharma R. R. Elevation changes of glaciers revealed by multitemporal digital elevation models calibrated by GPS survey in the Khumbu region, Nepal Himalaya, 1992–2008, Journal of Glaciology, 58, 648-656, 10.3189/2012JoG11J061, 2012. "The debris-covered areas are subjected to higher rates of lowering than are debris-free areas. One possible reason for larger differences between them could be the difference in mean elevation (5102 and 5521 m a.s.l. for debris-covered and debris-free area respectively)"

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, 10.5194/tc-5-349-2011, 2011. " Overall ice loss is estimated to be >0.6 km3 with an average surface lowering of 0.36 $\pm$ 0.07 m a$-$1 (...) between 1970 and 2007 (Table 3). The surface lowering for the debris-covered parts only is $-$0.39$\pm$0.07 m a$-$1, clearly showing that significant thickness loss occurs despite thick debris cover."

10. 3745/5 : Author's results about mass gain in 1990s does not support previous studies (Gardelle et al., 2012a; Kääeb et al., 2012). Because mass gain period in Gardelle et al. (2012a) and Kääb et al., (2012) are 1999–2008 and 2003–2008 respectively. The periods of them are almost after 2000s.

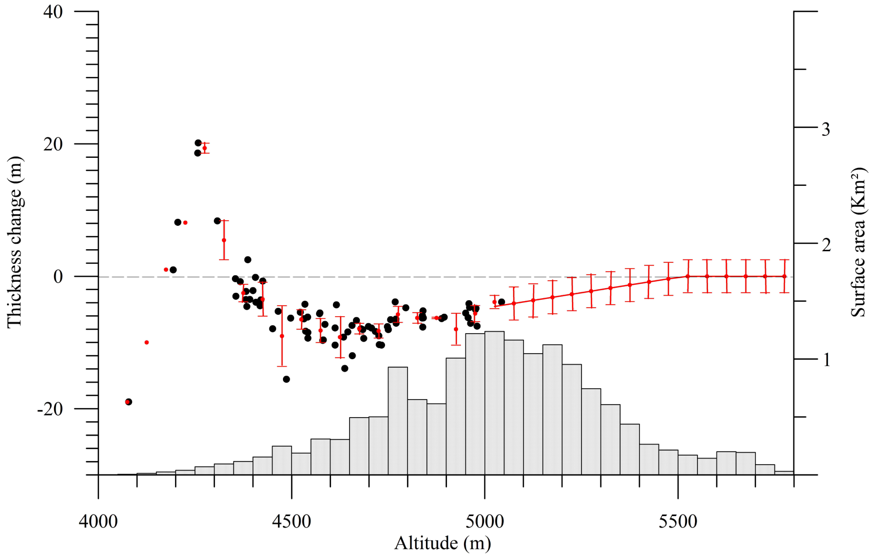
We agree and the sentence has been removed

Interactive comment on The Cryosphere Discuss., 6, 3733, 2012.



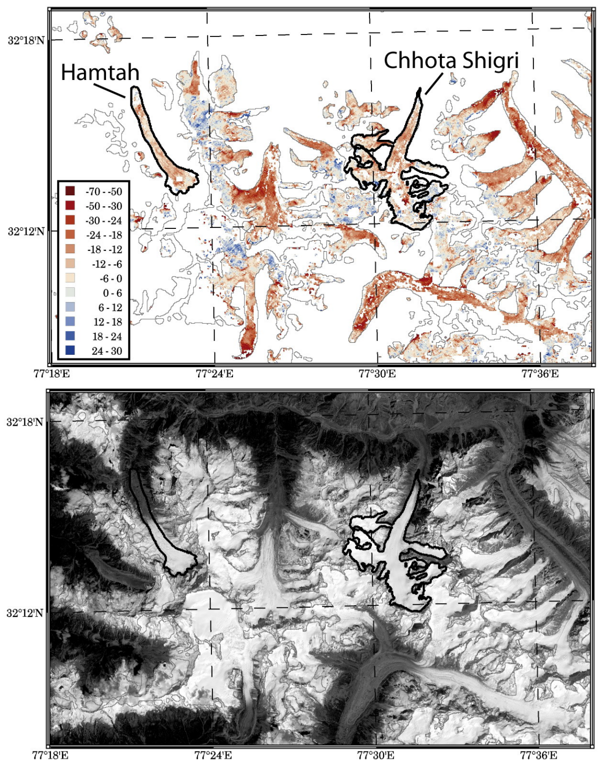
Elevation changes (dh) of CS Glacier between 1999 and 2011 for the main trunk (blue triangles) and the tributaries (red dots). The cumulative hypsometry (%) is shown as a blue dashed line (main trunk) and a red dashed line (tributaries). Error bars on dh were calculated using the number of valid measurements of dh in each 50-m altitude interval and taking into account a correlation length of 500 m (~12 pixels).

Fig. 1.



40
20
0
-20
Thickness change (m)
3
2
1
Surface area (Km²)
4000
4500
5000
5500
Altitude (m)

Fig. 2.



Hamtah
Chhota Shigri
32°18'N
32°12'N
77°18'E
77°24'E
77°30'E
77°36'E
-70 - -50
-50 - -30
-30 - -24
-24 - -18
-18 - -12
-12 - -6
-6 - 0
0 - 6
6 - 12
12 - 18
18 - 24
24 - 30

Fig. 3.