Response to T. Nuimura (Referee)

(Original comments are in bold, our replies are in standard font.)

I recommend to evaluate spatial distribution of surface elevation change using Pleiades and SPOT HRS derived DEMs. It enables several validation of your evaluated result.

Given the short time separation between the DEMs (less than 2 years between the SPOT5 DEM from January 2011 and the Pleiades-1A DEM from November 2012), we do not think it is relevant to compute the glacier-wide geodetic mass balance. There are two main reasons. (1) The expected signal of elevation change is small. The cumulative mass balance for those two years is only -0.21 m w.e. yr^{-1}, so if the field mass balance is unbiased, we are looking for a glacier-wide 2-year mean elevation change of just 0.3 m. This signal is smaller than the expected accuracy of this DEM comparison. From our experience with the SPOT5 DEMs in various regions, it would be difficult to reach an error lower than ±1 m. (2) The second reason is that the shorter the time separation between the DEMs, the larger the errors due to the unknown density of the snow/firn/ice gained or lost. This has been clearly demonstrated by Huss (2013) [Huss, M. Density assumptions for converting geodetic glacier volume change to mass change. The Cryosphere 7, 877–887 (2013)].

With our well-validated Pleiades DEMs from November 2012, in 4-5 years, we will be in a good position to acquire a similar dataset to compute the geodetic mass balance with the level of accuracy needed to check the cumulative glaciological mass balance as recommended in Zemp et al. (2013) [Zemp, M. et al. Reanalysing glacier mass balance measurement series. The Cryosphere 7, 1227–1245 (2013)]. This reference is now included in the revised manuscript.

Specific comments

P3344/L10–11: Could you show me the mean and standard deviation of density?

Done in the Mass balance section, section 4.1 where two sentences have been added for densities measured in the ablation zone:

"Snow densities are not very spatially or temporally variable with average values of 370 kg m^{-3} (standard deviation of 30 kg m^{-3}) below 5600 m a.s.l."

and in the accumulation area:

"Snow densities ranged from a mean of 380 kg m^{-3} (standard deviation of 30 kg m^{-3}) at 5700-5800 m a.s.l. to 450 kg m^{-3} (standard deviation of 10 kg m^{-3}) at ~6330 m a.s.l."

P3344/L12: In Figure 1, the number of stakes looks like 38. If stakes of outside Mera Glacier included, it is 45. Please check it.
P3344/L22: Does the points surface mass balance at outside of Mera Glacier also included in this glacier-wide mass balance calculation?

The total number of ablation stakes is indeed 45 and not 44 as initially written (now corrected in text and Table 1), including stakes located outside the Naulek branch of Mera Glacier. This latter stakes have been included in the mass balance calculation, because they are consistent with the stakes of Naulek branch, and needed to evaluate the mass balance gradient during years where many stakes have been buried by snow. The text is now clarified and includes additional sentences:

"Stakes are sometimes lost, buried under snow or broken by wind or climbers but our observation network allowed for a minimum of 17 point mass balance measurements in 2011-2012 (reading of 14 ablation stakes and 3 accumulation measurements performed) to a maximum of 31 in 2008-2009 (reading of 27 ablation stakes and 4 accumulation measurements performed). Ablation measured at stakes located on Naulek Glacier outside the Naulek branch of Mera Glacier are consistent with ablation measured at the Naulek branch stakes (inserted on similar slopes with same aspect, Fig. 2). Those stakes have thus been included in the mass balance calculations to increase the number of ablation measurements especially during years where this number was low (i.e. 2009-2010 and 2010-2011)."

P3345/L6–8: Mass balance as a function of altitude with regression line in Pokalde Glacier should be also shown like Mera Glacier (Figure 3). The figure also enables to judge the uncertainty of mass balance gradient in Pokalde Glacier with narrow elevation range (P3351/L20-21).

Please find below the requested figure A, for years 2009-2010 and 2011-2012, and for the two-year period 2010-2012. Actually, due to a thick snow cover on 20 October 2011, most of the stakes were buried by snow, and only one single 2010-2011 b_a measurement was available, preventing us from calculating directly the 2010-2011 annual glacier-wide mass balance (explaining why the mass balance gradient had not been reported in Table 2, in the original manuscript). To retrieve the 2010-2011 mass balance, the two-year 2010-2012 mass balance has been derived from field measurements following the method described in section 4.1, giving a mass balance of -1.23 m w.e. over the period 2010-2012 (Fig. A). Considering that the 2011-2012 glacier-wide mass balance is -1.12 m w.e., the 2010-2011 glacier mass balance is thus -1.23 – (-1.12) = -0.11 m w.e. This is now clearly specified in a note [a] below Table 2 referring to 2011-2012 mass balance:

"[a]Calculated by difference between 2010-2012 and 2011-2012 glacier-wide mass balances [B_a(2010-11) = B_a(2010-12) - B_a(2011-12)], due to a lack of measurements in October 2011 where heavy snow falls had covered the stakes. The 2010-2012 mass balance has been calculated following the method described in section 4.1."

Since our paper focuses on Mera Glacier and not on Pokalde Glacier where measurements are presented only for comparison purposes, we prefer not to add this figure A in the revised manuscript, because it gives an illustration of the method used to calculate the mass balance (already given for Mera Glacier in Fig. 3) but does not bring any substantial information.

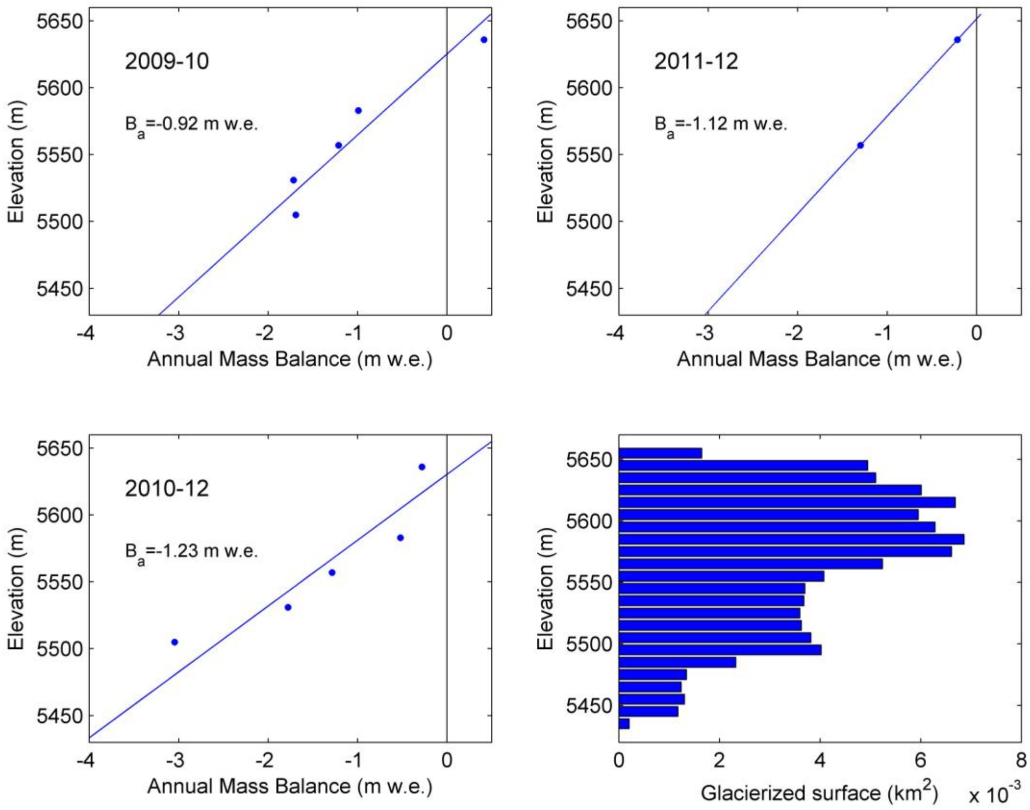

Figure A: 3 first panels: point mass balance (dots) as a function of altitude derived from field measurements (stakes, drillings or pits) on Pokalde Glacier, for two distinct years 2009-2010; 2011-2012 and for the two-year period 2010-2012. Measurements were performed on 20 November 2009, 26 October 2010, 20 October 2011 and 12 December 2012. The glacier-wide mass balance (B_a) is given for each time period. Bottom right panel: hypsometry of Pokalde Glacier.

P3346/L3: How many stakes did you use? Is is careless mistake?

There are effectively 47 velocity measurements (45 ablation stakes + 2 accumulation stakes surveyed). The sentence has been re-phrased to avoid any confusion:

“Annual surface ice velocities have been measured every year in November on Mera Glacier by determining the displacement of 47 stakes (45 ablation stakes and 2 accumulation stakes) using a Differential Global Positioning System (DGPS) (Topcon devices, dual frequency, 1-sec acquisition frequency, ~30-sec acquisition time at every stake).”

P3346/L4: Please include information about GPS instrument and accuracy in specification. Is the DGPS measurement accuracy _0.1 m? (P3346/L21)

Topcon devices, dual frequency, 1-sec acquisition frequency, ~30-sec acquisition time. This is now specified in the revised manuscript (see the reply to the previous comment). A new sentence dealing with accuracy has been added:

“The accuracy of DGPS measurements depends on the number of operating satellites, their geometrical configuration in the sky, the distance to the DGPS base station and the acquisition frequency and duration; maximum uncertainty is ±0.1 m for horizontal and vertical components, the horizontal uncertainty being usually lower.”

P3347/L4–P3348/L8: I recommend you to evaluate surface elevation change between Pleiades-1A DEM in 2012 and SPOT5 HRS DEM in 2011? If you evaluate spatial distribution of elevation change, you can validate mass balance gradient and kinematic ice flux combination with elevation change and field measured ice density (P3344/L10).

As stated above, over a 22-month period, even if the annual glacier-wide mass balance was very negative (which was not the case in 2010-11 and 2011-12), the elevation changes would be smaller or in the range of uncertainties from DEM differencing.

Second, glacier-wide mass balance, the variable generally inferred from DEM differencing, can only be compared to the same quantity measured in the field. It is much more complicated task to validate the field-measured mass balance gradient using remote sensing data. It would require a good knowledge of the spatial distribution of elevation changes (from accurate DEMs) but also ice fluxes at several flux gates across the glaciers (e.g., Reynaud, L., Vallon, M. and Letreguilly, A.: Mass-balance measurements: problems and two new methods of determining variations, Journal of Glaciology, 32(112), 1986). Such a method implies to differentiate ice fluxes (always uncertain due to error on the bedrock topography and the poor knowledge of the amount of basal sliding) and leads to large uncertainties as shown recently for the very well surveyed Mer de Glace in the European Alps (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, Journal of Glaciology, 58(209), 501–512, 2012).

Finally, we are wondering whether elevation changes derived from DEM acquired just 2 year apart can serve to validate field data. We believe that for a small-to-medium size glacier such as Mera, field data may be used to validate volume change derived from DEM differencing. Only in a few years, with the availability of a new high resolution and accurate Pleiades DEM, we will be in position to confront glaciological and geodetic mass balances for Mera Glacier.

P3347/L18–26: Extent of DGPS track is important information for readers to evaluate reliability of co-registration. Could you include track of DGPS measurement and footprint of SPOT HRS derived DEM and HRG image in Fig.1?

The location of the DGPS track has been added to Figure 1.

P3347/L27–P3348/L2: How much RMSE value of the 25 GCPs in triangulation processing?

Added now :

“The root mean square (RMS) residuals for those 25 GCPs were 1.36 m and 1.24 m for the Easting and Northing map projection coordinates, about twice the pixel size of the Pleiades images and half the pixel size of the SPOT5-HRG image.”

P3350/L7–8: Does it mean Recco reflector brown away?

Recco reflectors were systematically tied to 3-m long bamboo accumulation stakes, preventing them from being blown away. This is now clearly mentioned in the revised manuscript.

P3351/L3–7: Figure about spatial distribution of mass balance make easy to understand the relation between aspect and mass balance. Could you make new figure about it?

It would be nice to produce such a figure but actually, even though the stake network is dense on this small to medium-size Mera Glacier (from a minimum of 17 to a maximum of 31 measurement points in 2011-12 and 2008-09 respectively, specified in text, depending on the number of lost or buried stakes), the measurement network is not always able to accurately capture the spatial variability of the mass balance. Consequently, it is presently not possible to provide such a figure with a reasonable accuracy.

P3351/L19: Although, you mentioned drier climate makes mass-balance gradient large, Is is inverse? I think mass-balance gradient tend to small in drier region.

Because Pokalde Glacier receives less precipitation than Mera Glacier, the 5500-5630 m a.s.l. area where measurements are performed is often in summer covered partially by snow in its highest part and partially by exposed ice in its lowest part, enhancing the absorption of short-wave radiation. Consequently, the mass balance gradient is large, due mainly to the fact that the altitudinal range considered here encompasses the area of the glacier where there is a transition between exposed ice and snow, at least in summer. This is now specified in the revised version:

"(ii) it is located inside the mountain range and thus submitted to a much drier climate than Mera Glacier. The 5500-5630 m a.s.l. area where measurements are performed is often partly covered by snow, and partly by exposed ice enhancing short-wave radiation absorption. The fact that the altitudinal range considered here often encompasses the snow-ice transition zone explains why the mass-balance gradient is steepened;"

P3354/L8–12: Could you show me the area in figure. This is critical information for evaluating reliability of ice flux in eq.(3).

Both areas contributing to CS_5520 and CS_5350 are now shown in Fig. 9 of the revised MS. Actually, for this revised manuscript, we reevaluated these two zones with accuracy, following the topography provided by the map and inspecting again visually some photographs. Table 3 displays the revised values for ice fluxes obtained from the mass balance method accounting for the revised feeding areas of CS_5520 and CS_5350 as well as the revised mass balance gradients for 2011-2012. The resulting fluxes are not significantly different from the original values and the corresponding discussion has thus not been changed.

P3354/L25–26: Accumulation area used to calculation of eq.(3) might be helpful for judging reason of the bias. And surface elevation from remote sensing DEMs would also helpful for validating this result

The area used to calculate the ice fluxes from eq.(3) is now shown in Fig. 9. As stated above the time separation between our DEMs is too short to infer any useful measurement of elevation changes.

P3354/L27–P3355/L4: This sentence is difficult to understand. I might misunderstand it. Does it mean that relatively large ablation made ice flux large in last one or two decades, and then recent small ablation make ice flux small (although it has time lag due to response time)? However, if we consider recent negative trend of glacier-wide mass balance, glacier thickness was larger than now in last one or two decades. It means glacier flow was higher in last one or two decades.

With the mean annual 2007-2012 mass balance (-0.08 m w.e.), the ice flux obtained by the mass balance method is equal to 0.73x10^6 m^3 ice yr^{-1} through CS_5520 and 0.56x73x10^6 m^3 ice yr^{-1} through CS_5350 compared to the kinematic fluxes equal to 0.38x10^6 m^3 ice yr^{-1} and 0.18x10^6 m^3 ice yr^{-1} through both sections respectively. The current ice flux i.e. the kinematic flux is therefore more negative than the ice flux obtained from the mean 2007-2012 mass balance. Consequently, the current ice-flux would correspond to a mass balance more negative than the mean observed 2007-2012 mass balance. Considering that the current ice flux is a kind of proxy of the mean decadal state of balance of the glacier, it means that the mean mass balance of Mera Glacier over the last 1 or 2 decades is below -0.08 m w.e. and above -0.48 m w.e. (= 2009-2010 mass balance where the ice fluxes through CS_5520 and CS_5350 are 0.27x10^6 m^3 ice yr^{-1} and 0 respectively i.e. smaller than the kinematic ice fluxes – Table 3). Some clarifications have been provided; see the answer of the comment below regarding again ice fluxes.

P3355/L23: It is difficult to say it from only one data (Nov. 08 – Apr. 09). The assertion should be weakened. (ex. append phrase like a "further observations are necessary to confirm it")

It is not only one data, there are also data between Nov 2012 and Apr. 2013, and 4 winters with regular data on Pokalde Glacier. Anyway, the suggested phrase has still been added at the end of the corresponding sentence.

P3357/L6–7: Did you mention it is due to small area right?

Yes, and now mentioned in the sentence.

P3357/L21–23: The reason of bias has not yet clarified. You should weaken the assertion.

There is probably a misunderstanding here. Actually, it is not a bias here, but a difference. In one hand, the kinematic fluxes through CS_5520 and CS_5350 are lower than the fluxes obtained with a mass balance of -0.08 m w.e. (= mean 2007-2012 mass balance) and higher than the fluxes obtained with a mass balance of -0.48 m w.e. (= 2009-2010 mass balance). Consequently, the mean balance state of Mera Glacier over the last 1 to 2 decades is comprised between both values. The sentence has been clarified here to answer this comment regarding the ice fluxes and also the previous comment above:

"The kinematic fluxes through CS_5520 and CS_5350 are lower than the fluxes obtained with a mass balance of -0.08 ± 0.28 m w.e. yr^{-1} (= mean annual mass balance from 2007 to 2012) and higher than the fluxes obtained with a mass balance of -0.48 ± 0.28 m w.e. yr^{-1} (= 2009-2010 mass balance) (Table 3). Consequently, mean decadal mass-balance conditions of Mera

Glacier are comprised between both above-mentioned values in agreement again with Gardelle et al. (2013)."

P3367/Table 2: To evaluate uncertainty of mass balance gradient in Pokalde Glacier, additional information is necessary (the standard deviation calculated from 2 data is nonsense). As I noted previously, please make figure about mass balance as a function of altitude with regression line in Pokalde Glacier.

Please see the Figure A above and the corresponding comment. The standard deviation of the mass balance gradient has been removed from Table 2.

P3372/Figure 3: The particular one point (noted in P3351/L7–9) is indistinctness. If you add spatial distribution of mass balance as my previous comment, it is not necessary to color.

The Figure of mass balance distribution has not been added (see the corresponding comment above), but the peculiar point discussed in P3351/L7-9 has been displayed as a blue square highlighted by a red contour (instead of a dot) to be more visible in Fig. 5 (=old Fig. 3) and is also visible in Fig. 2 (red dot).

Technical corrections

P3369/Figure 1: Label text of coordinates, contour line of Pokalde Glacier are too small. Label of Namche Bazar is hidden by subset image of Pokalde Glacier. There are several stake outside of Mera Glacier.

The maps of Mera and Pokalde glaciers are now shown in Fig. 2 and 3 respectively and Fig. 1 shows only the studied area. The stakes outside of Mera Glacier (Fig. 2) have not been removed because they are accounted for in mass balance calculations as described in the revised MS.