Response to Reviewer's Comments – 2 April 2015

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J.M. Shea et al.

We thank Ben Marzeion for his second reading of the manuscript, and for his attention to the calibration and validation of the mass balance model. Our response to his comment is given below in **bold**. Revised text in the resubmitted manuscript is given in *italics.*

Reviewer 1: Ben Marzeion

I am impressed by the amount and detail of additional work the authors have done in response to all the reviewers' questions and suggestions. All the minor comments I had were carefully taken into account, as well as the first and third (of my three) general comments.

The only point that remains a bit unclear to me is the response to my second general comment, regarding the calibration procedure. I now understand that the 20 parameter sets were generated randomly, and I agree that this is better than "handpicking" parameter values. However, I am still not convinced that the calibration is robust. The authors argue that "100 sets would probably reveal the same patterns as 1000"; this may or may not be true - my point is that it probably will be very hard to find any robust patterns with 20 sets. A robust calibration would lead to good performance also in an out-of-sample validation, which is why I suggested that the validation (as described in Sect. 2.5) should be carried out for all 20 of the calibration runs. If this validation is more favorable for the calibration runs with low total scores than for those with high total scores, it would indicate that the calibration is robust; if the runs with low total scores in the calibration don't perform better than the ones with high scores, it would be indicative of overfitting (or at this low number of calibration runs, probably rather of a random result).

If it turns out that the calibration is not robust, I don't think it would break the study - the spread of the 20 calibration runs (e.g. in Fig. 10) would then be a good first indication of the parameter uncertainty. I think it is very useful to know which source of uncertainty is dominant (e.g. parameter uncertainty, scenario uncertainty, ensemble uncertainty, etc.) because it indicates where we perhaps should focus our work.

Response: Thanks for your appreciation of our efforts! The question of validation for all 20 parameter sets is difficult to deal with, as we had originally intended to only validate the calibrated model and so some of the outputs are not available for all model runs. There were four validation criteria, and in this response we discuss each of these in turn:

- **ice depths**
- **annual mass balance and mass balance gradients at Mera Glacier**

- **decadal glacier area change**
- **basin-wide mean annual mass balance**

Ice Depths

We have updated the ice depth validation figure to include all modeled ice thicknesses from the 20 calibration runs (Figure R1). New text in section 3.2.3 describes the low sensitivity of the modeled ice depths to the choice of parameters:

> **"Modelled ice depths do not appear to be highly sensitive to the range of model parameters used in the 20 calibration runs, though variability is higher for Mera Glacier than for Changri Nup Glacier."**

Annual Mass Balance and Mass Balance Gradient

The mean and standard deviation of all 20 calibration runs for annual mass balance at Mera Glacier was given in the original manuscript (Figure 13). As there was no overlap between the observed mass balance at Mera Glacier (2008-2013; Wagnon et al., 2013) and the APHRODITE climate fields (1961-2007), we can only comment that the spread in modeled annual mass balance is lower than the observational error.

As was done in the original manuscript, we have extracted the mass balance gradients for 1) the entire Dudh Kosi catchment between 5000 and 6000 m; 2) Mera Glacier only, between 5350 and 5600 m; and 3) Naulek Glacier only, between 5350 and 5600 m. Figure R2 below shows boxplots of the mass balance gradients calculated for the 20 runs, with the selected Run 5 results highlighted.

Mass balance gradients for Run 5 tend to be on the higher side for all three cases. Wagnon et al (2013) found ablation zone mass balance gradients at Mera Glacier of 0.32 to 0.58 m w.e. (100 m)$^{-1}$, and at Naulek Glacier of 0.72 to 0.97m w.e. (100 m)$^{-1}$. The text in the section 3.2.1 (Mass Balance has been revised to account for the additional validation:

> **"The range of mass balance gradients for the other 19 parameter sets ranges from 0.10 to 0.34 m w.e. (100 m)$^{-1}$. The mass balance gradient from run 5 gives a basin-wide ELA at approximately 5500 m, which agrees with previously published estimates (Williams, 1983; Asahi, 2010; Wagnon et al., 2013). Mass balance gradients at Mera and Naulek glaciers are approximately 0.40 and 0.68 m w.e. (100 m)$^{-1}$, respectively, between 5350 and 5600 m. These values compare well with the gradients of 0.48 and 0.85 m w.e (100 m)$^{-1}$observed over the same elevation range at Mera and Naulek between 2007 and 2012 (Wagnon et al., 2013). Calculated mass balance gradients from the different parameter sets range from 0.31 to 0.35 m w.e (100 m)$^{-1}$ at Mera Glacier, and from 0.46 to 0.72 m w.e (100 m)$^{-1}$ at Naulek Glacier (Figure 13).**

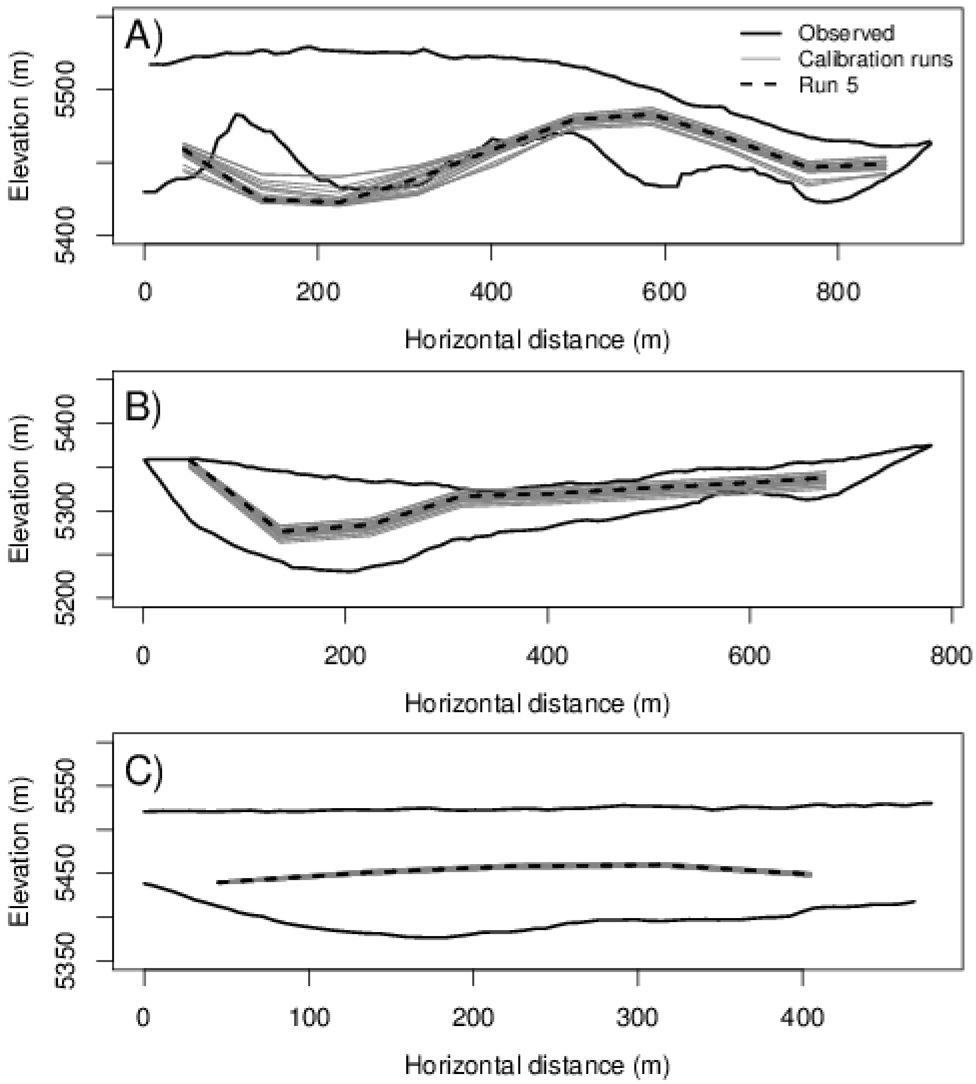

Figure R1 (replaces Figure 14 in the manuscript): Glacier depths estimated from transverse ground-based GPR surveys and the mass balance and redistribution model, for (A) profile at 5350 m on Mera Glacier, (B) profile at 5520 m on Mera Glacier, and (C) profile at Changri Nup glacier (Figure 1). The results of the calibrated model run are given as a black dashed line.

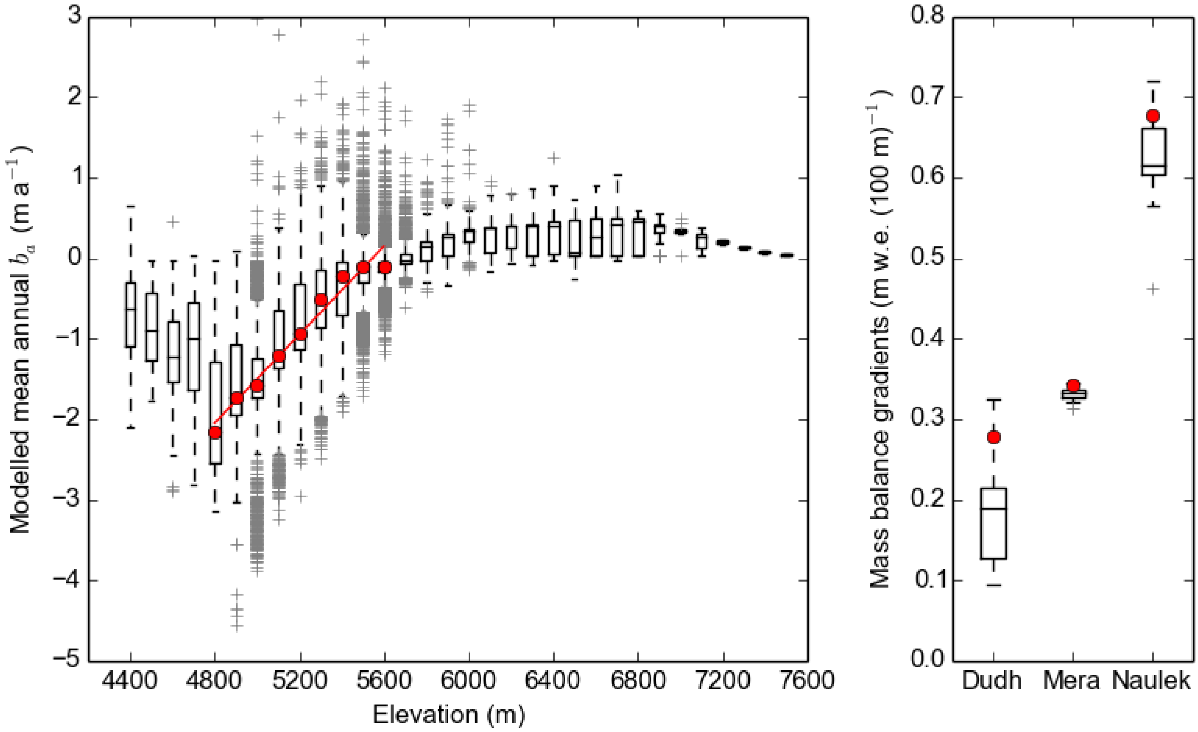

Figure R2 (Replaces Figure 12 in the manuscript): Left: Boxplots of modelled mean annual mass balance (m w.e. yr −1) calculated for 100 m intervals (1961 - 2007) for the entire Dudh Koshi basin (Run 5). Calculated mass balance gradient of 0.27 m w.e. (100 m) $^{-1}$ between 4850 and 5650 m is shown in red. Right: Boxplots of mass balance gradients calculated for all 20 calibration model runs for the entire Dudh Kosi (between 4850 and 5650 m), Mera Glacier (between 5350 and 5600 m), and Naulek Glacier (between 5350 and 5600). The gradients calculated for Run 5 are shown in red.

Decadal Glacier Area Change

In the original manuscript, modeled decadal glacier area change from 1980 to 2010 was compared against the observed area change derived from Landsat inventories. We considered only areas below 5500 m, and the calculations of area change were done only during the calibrated model run. As a result, the 19 remaining calibration runs have been redone to obtain the required area change information.

Figure R3 shows the area change statistics for all 20 calibration runs and three separate periods: 1980 – 1990, 1990 – 2000, and 2000 – 2007. The change in average modeled glacier area between 1 November and 31 January was used for these calculations. As indicated in the manuscript, the rate of glacier change increased from 1980 – 1990 to 2000 – 2007. The paragraph describing the validation has been revised in the manuscript:

A small figure and new text in the manuscript describes the additional validation tests:

> **"Below 5500 m, the observed rate of glacier area change in the Dudh Kosi was -0.61% yr^{-1} between 1990 and 2000, and -0.79% yr^{-1} between 2000 and 2010. For the 20 parameter sets, modelled rates of glacier area change below 5500 m (Figure R3) vary between -0.24 and -0.41% yr^{-1} (1990 - 2000) and -0.54 and -0.85% yr^{-1} (2000 - 2007). The calibrated run (Run 5) gives area change rates of -0.36 and -0.75% yr^{-1} for the 1990 - 2000 and 2000-2007 periods, respectively."**

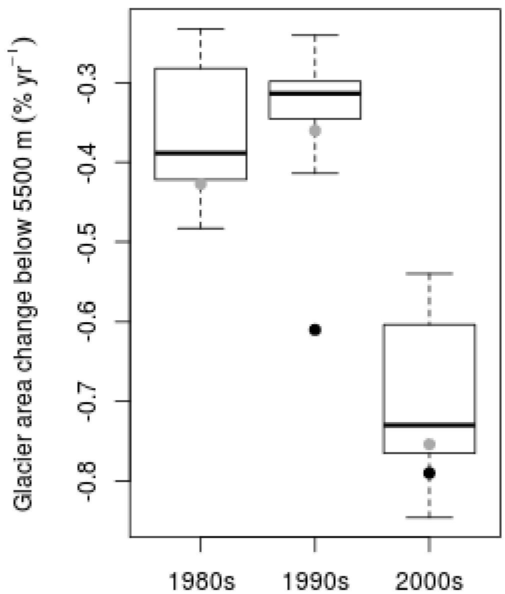

Figure R3: Rates of historical glacier area change below 5500 m (% yr^{-1}) from observations and 20 model runs. Remotely sensed rates of glacier area change and Run 5 results are shown as black and gray points, respectively. The 1980s inventory contained inaccuracies related to the misclassification of snow as glacier ice, and an observed rate of change from 1980 to 1990 is not included here.