

Point-to-point reply to the Reviewer#1 in red.

Reviewer#1.

General

The authors continue their earlier work on the mass balance (MB) of the Chhota Sigri glacier in the Lahaul-Spiti valley of Western Himalaya, India, within a tributary basin to the Indus river basin. Both existing MB results from field measurements (glaciological method) carried out during the period 2002–2023, and geodetic MB results from satellite imagery (ASTER and Pleiades) collected in 2003, 2014 and 2020, are used in the study.

Geodetic MB is generally considered more accurate since the data cover the entire glacier surface. In contrast, stake locations where annual accumulation or ablation is recorded may not yield data that are fully representative for the glacier-wide MB. Identifying and correcting for biases in field-based MB data thus forms an important component of ongoing evaluations of glacier mass balance data from many glaciated regions of the world.

In their reanalysis, the authors employ a nonlinear model yielding MB as a function of elevation originally devised by Liboutry (1974) and later employed by e.g. Vincent and others (2018). A linearly changing hypsometry of the glacier from year to year, based on the remote sensing data, is also employed. Comparison of results produced by the nonlinear model with traditional MB results (glaciological MB, profile method), shows that use of the model leads to a reduced bias in the field-based MB data, as demonstrated by comparing glacier-wide results with the geodetic results.

The authors obtain the convincing figure of -0.47 ± 0.19 m w.e. a⁻¹ for the average annual MB of Chhota Shigri during the period 2002–2023, corresponding to a cumulative mass loss of 9.81 m w.e. As noted by the authors, the results are typical for this particular region of the Himalaya. The authors also devise a way of using the nonlinear model to estimate glacier-wide MB if only very few field measurements are available from a particular year. Moreover, the nonlinear model can be used to correct or remove suspicious point MB data resulting from mistakes in observations or other factors.

Overall, this manuscript presents carefully worked-out and bias-corrected MB results from one of the most important benchmark glaciers in the Himalaya, produced by an Indian-French research group that has been actively studying this glacier for more than 2 decades.

This reviewer does not have specific criticisms of the data or methodology, except to mention that it would be valuable to include a discussion of the likely reasons for the bias in the glaciological measurements (w.r.t. geodetic) and why it switches sign between the two periods considered (Table 2, p. 18), from a negative bias of -0.11 m/a in 2002–2014 to a positive bias of $+0.33$ m/a in 2014–2020.

Suggestions for English language improvement on the manuscript are included below.

We thank the reviewer for carefully assessing our manuscript and providing constructive comments/edits. Below, we provide point-to-point replies to each of the concerns in red. The changes made in the manuscript are shown in *italics* here and in red colour in the manuscript. The manuscript is proofread for grammar issues with a special focus on the usage of the articles. We invite the reviewer to go through our response and the revised manuscript.

We understand the reviewer's concern about investigating the source of the systematic biases in glacier-wide MB estimated from the traditional method and its sign conversion after 2014. In the Discussion section “5.1: Biases in glacier-wide mass balances and performance of nonlinear model”, we have discussed that the possible reason for the systematic biases might be the poor accumulation data in some years, especially post-2014 (in some years, no accumulation measurements could be done). The poor sampling post-2014 is probably the reason for the bias shift post-2014. However, this does not prove that the bias mainly comes from the accumulation area. In the Himalaya, this kind of bias has been thoroughly analysed only on Mera Glacier (Nepal). Wagnon et al. (2021) did a thorough analysis and tracked the source of bias in glacier-wide MBs of Mera Glacier. They compared the surface-specific mass balance from the traditional glaciological method of a certain zone of the Mera Glacier with the surface-specific mass balance from the ice-flux method. They concluded that the systematic biases in the Mera Glacier MB series are mainly due to an overestimation of the accumulation above 5520 m a.s.l., likely due to a measurement network unable to capture its spatial variability. Such an analysis is impossible on Chhota Shigri Glacier due to insufficient data to estimate the surface-specific MBs the using ice-flux method. However, we thank the reviewer for highlighting this. We will surely improve our field measurements to address this issue in future. We highlighted this in the revised manuscript and added a small paragraph in “Section 5.1: Biases in glacier-wide mass balances and performance of nonlinear model”.

Line: 521-527:

“Wagnon et al. (2021) performed a thorough analysis on Mera Glacier (Dush Koshi Basin, Nepal) and identified the precise source of systematic bias in the glacier-wide MB by comparing the surface-specific mass balance calculated using the traditional glaciological method of a specific zone on the glacier with that derived from the ice-flux method (based on the mass conservation equation). Unfortunately, we could not conduct such an analysis in the current study due to insufficient data availability. However, future research will include this comparative analysis to uncover any systematic biases in the glacier-wide MB data series for the Chhota Shigri Glacier.”

Reviewer 2 suggested to include a figure showing the results from nonlinear model and against the in-situ observation. Hence, we compared the in-situ and modelled point MBs in a newly added section “Comparison of all in-situ and modelled point-MBs over 2003-2023” in the SI and developed two Figures; Figure S2 showing the modelled and observed, erroneous and extrapolated point-MBs against the corresponding elevations, and Figure S3: showing the differences between modelled and observed point-MBs, modelled and erroneous point-MBs and modelled and extrapolated point-MBs.

Line: SI

“Comparison of all in-situ, extrapolated and modelled point-MBs over 2003-2023:

Figure S2 shows the in-situ point-MBs (including the erroneous measurements), all extrapolated MBs (used in glacier-wide MBs estimated in the previous studies) and the modelled point-MBs against their corresponding elevations for each year between 2002 and 2023.” Figure S3 represents the difference between the modelled and extrapolated point-MBs, modelled and erroneous point MBs, and modelled and observed point MBs. The modelled point-MBs showed maximum differences with erroneous point-MBs ranging from -3.21 to 1.01 m w.e., with a mean difference of -0.74 m w.e. and a standard deviation (STD) of 1.33 m w.e. The differences between modelled and extrapolated point-MBs vary from -1.98 to 1.74 m w.e. with a mean difference of -0.15 m w.e. and an STD of 0.68 m w.e. While the differences between the modelled and observed point-MBs vary from -1.32 to 1.43 m w.e. with a mean difference of -0.02 and an STD of 0.40 m w.e. (Fig. S3). These large differences between modelled and extrapolated point-MBs, which are mostly from accumulation area, suggest that the extrapolation of point-MBs in the accumulation area is risky and can add some additional error in the glacier-wide MBs.

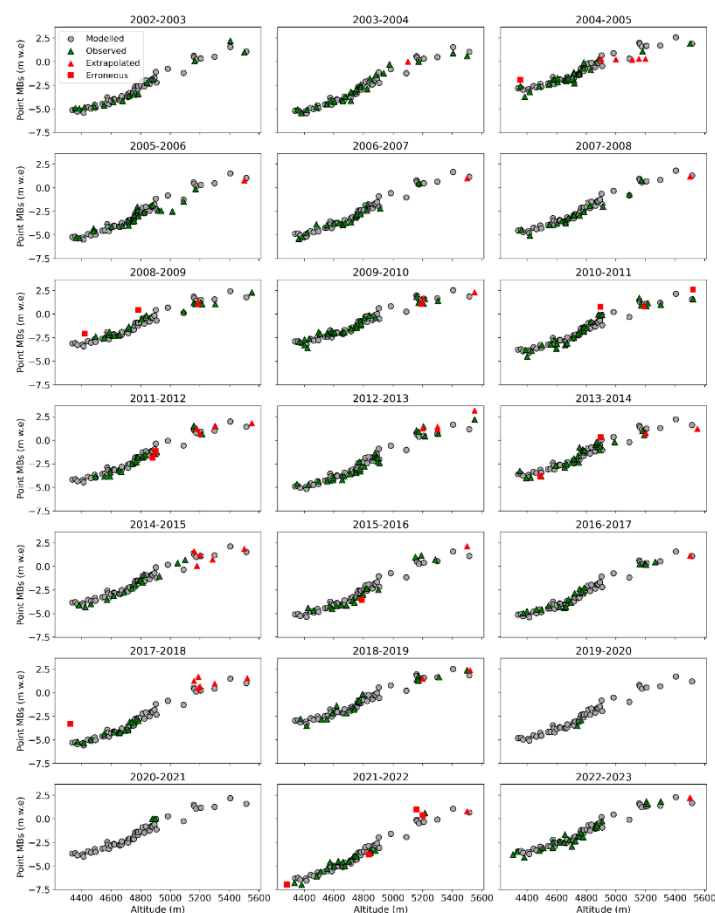


Figure S2: The observed (green triangles) and modelled (grey circles) point MBs against their corresponding elevations for the hydrological years between 2002 and 2023. The extrapolated (red triangles) and erroneous (red squares) point MBs are also shown.

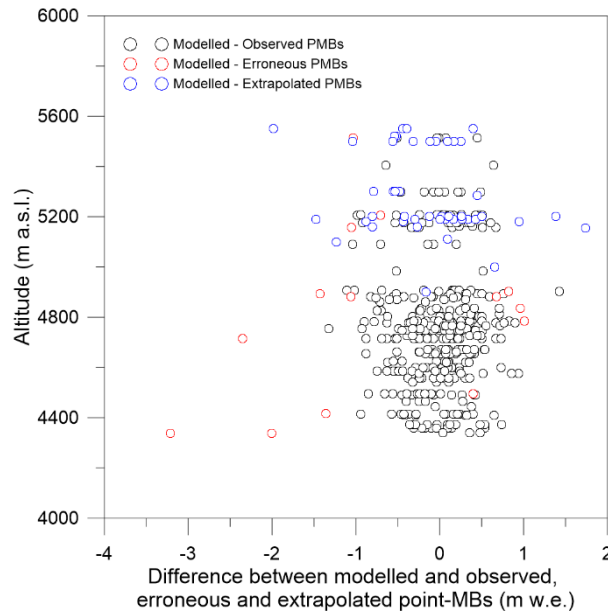


Figure S3: The differences between modelled point MBs and observed (black circles), erroneous (red circles) and extrapolated (blue circles).

Following this Figure S2 and S3, we have added a sentence in the section 5.1 of the revised manuscript.

Line: 541-551:

“The nonlinear model shows a much better agreement with geodetic MBs than the traditional method (Fig. 8; Table 2) mainly due to the (i) capability of the nonlinear model to better capture the spatial variability of surface MB from a heterogeneous, discontinuous and limited point MB data series than the traditional method (Vincent et al., 2018), (ii) correction/exclusion of erroneous measurements (section 3.3) and (iii) exclusion of the extrapolated ablation/accumulation points in the nonlinear model that might have introduced biases in traditional MB (Fig. S2). The extrapolated point-MBs in the accumulation area showed a difference ranging from -1.98 to 1.74 m w.e. between modelled and extrapolated, especially post-2014 (Fig. S2 and S3). The better performance of the nonlinear model suggests that the extrapolation of point accumulations (in case of missing point measurements) in estimating the glacier-wide MB using the traditional method is risky.”

Title

using nonlinear model --> using a nonlinear model

Done.

L15: from traditional glaciological method --> obtained with the traditional glaciological method

Done.

L20: Further, nonlinear model is also used...

-->

Further, the nonlinear model is also used....

Done.

L23-24

The nonlinear model outperforms the traditional glaciological method...

Is this appropriate wording? The nonlinear model uses data collected with the traditional method and improves on the results, so these are not two independent methods.

The wording is fine. Figure 5 clearly shows the difference between the nonlinear model and the traditional glaciological method applications. Yes, the input data for both the methods is the same (point ablation and accumulation observations) but their use to estimate the glacier wide mass balance is different. The points mass balances are decomposed in spatial and temporal terms in the nonlinear model while they are used directly in traditional glaciological method.

L37-43

Drop "the" in: "to understand the possible glacial hazards"

Done.

L41

or measured using field-based glaciological method

-->

or measured using the field-based glaciological method

Done.

L47

cannot be used to understand...

-->

cannot be used to study...

Done.

L48-49

Conversely, field-based traditional MBs —estimated at annual/seasonal scale—directly respond to local meteorological conditions.

--> (suggestion)

Conversely, field measurements using standard methods (ref) yield data on the seasonal/annual response of glacier mass balance to local meteorological conditions.

Done.

Now this sentence is,

Line 50-52:

“Conversely, field measurements using standard methods (Østrem and Stanley, 1969) yield data on the seasonal/annual response of glacier MB to local meteorological conditions (Zemp et al., 2015).”

L53-54

For annual glacier-wide MB estimation, traditional field-based glaciological method has been used in the Himalaya (Azam et al., 2018).

-->

Maybe "field-based" can be dropped in this sentence - it is already mentioned in L48

Done.

L59

representative of surrounding areas

-->

representative of the surrounding areas

Done.

L60-61

thus, the snow avalanche inputs are not included,

-->

thus, snow avalanche inputs onto valley glaciers are not included

Done.

L62-63

controls snow blowing/deposition

-->

controls snow drift and deposition

Done.

L68

due to accessibility \diamond due to accessibility issues (might be better)

Done.

L80

hence ignoring --> but ignored

Done.

L102-103

Not clear here what: "over medial and lateral moraines from 4100 to ~4900 m" means - obviously there is debris on those moraines, otherwise they would not be moraines.

Perhaps it was not clear. We meant that in our 12% debris cover estimate we included the lateral moraines. Now, the slightly revised sentence is "Based on the most updated map obtained in September 2020, 12% of its total surface area is covered with debris between the snout and 4500 m a.s.l., including medial and lateral moraines from 4100 to ~4900 m a.s.l. and a debris-covered eastern tributary glacier (Fig. 1)."

L134

inserted up to 10 m inside the glacier ◇ inserted up to 10 m into the glacier

Done.

L156

some years were undersampled

-->

the mass balance was undersampled in some years.

Or:

a limited number of MB measurements could be carried out in some years.

Done. Now it is "...a limited number of point MB measurements could be carried out in some years."

L156-157

"when" instead of "where" – twice

Done.

L158

before the storm. --> before the September storm.

Using 'September storm' may mislead the reader as storms are not the characteristic of September month. It is already said in the previous sentence "...snowstorms like on 22-24 September 2018...". We think the sentence is clearer in its original form.

L166

spatial effect term --> a spatial effect term

temporal term --> a temporal term

Done.

L168

Parentheses missing around equation number (2)

Done.

L169

the spatial effects --> the spatial effect

Done.

L172

by the maximum --> and the maximum

Done.

L175

each location --> should this rather be “all point locations” ?

Done.

L182

over minimum ten years --> over a minimum of ten years : probably better

Done.

L210-211

hence, the nonlinear model cannot be run.

-->

hence, the nonlinear model cannot be run for this mass-balance year.

We rephrased like “hence, the nonlinear model cannot be run for this hydrological year.” as the mass balance is observed over the hydrological year, defined in Line 169-170.

L215

on 6 September 2021 Sentinel image --> on a 6 September 2021 Sentinel image

Done.

L216-217

It is to be noted --> It should be noted

Done.

L218

using nonlinear model --> using the nonlinear model

Done.

L222

conducted hence --> conducted; hence

Done.

L222-223

The two grid cells selected are 200x200 m and the zero values picked for them should thus not be referred to as “point MBs”

Thanks. Yes. Corrected.

L224

on delineated --> on the delineated

The background is Sentinel image --> The background is the Sentinel image

Done.

L227-228

The calculation of glacier-wide MB needs to get a spatial distribution of a_i over the whole

surface area of the glacier.

-->

For the calculation of glacier-wide MB a spatial distribution of α_i over the whole surface area of the glacier is needed.

Done.

L241-242

“As expected, the residuals followed a normal distribution with a standard deviation (STD) of 0.35 m w.e. a^{-1} (Fig. 4B).”

- This sounds like the STD value of 0.35 had been estimated beforehand, which is unlikely to be the case.

Yes, the STD value of 0.35 was estimated first with all the available data and then after removal/correction of the suspicious point MBs. A sentence has already given in section 3.3:

Line: 276-277

“The standard deviation of the residuals from the nonlinear model *was* reduced from 0.35 to 0.30 m w.e. a^{-1} after correction/removal of suspicious point MB measurements.”

L248

wrong and discarded --> erroneous and were discarded : probably better

Done.

L248-249

The wrong field measurements come from different years

-->

The erroneous data were collected in different years

Done.

L251

reduced --> was reduced

Done.

L255

from glacier snout --> from the glacier snout

Done.

L287-290

This sentence is a bit unclear, suggest rewording to:

“Further, the geodetic MBs of the western tributary of Chhota Shigri (the WT glacier, see Fig. 1), which fragmented sometime around 2012, were estimated from area-weighted comparison with Chhota Shigri, for direct comparison with traditional and nonlinear MBs.”

That is, if this reviewer understands the meaning of the sentence correctly, which is not certain.

Thanks for the suggestion. Perhaps the sentence was not clear. For clear message, we re-wrote it as:

Line: 314-317:

“Furthermore, the geodetic MBs included both the WT glacier, which fragmented around 2012 (Srivastava et al., 2022), and the main Chhota Shigri (area-weighted) (Table 1) for a direct comparison with the traditional and nonlinear MBs that include the WT glacier.”

L320

two periods when the geodetic MBs were calculated

-->

two periods for which the geodetic MBs were calculated

Done.

L350

Reference to Table 3 before Tables 1 and 2 have been mentioned.

Checked carefully, the referencing of Tables is fine.

L370

September 2020 year \diamond September 2020 each year (?)

The debris cover area was estimated corresponding to the September 2020 year. The wording is fine and clear.

L463

observed --> collected

Done.

L489-490

or observers not experienced enough.

-->

or observers not being sufficiently experienced.

Done.

L509-511

“The outperformance of the nonlinear model suggests that the extrapolation of point accumulations (in case of missing point measurements) in estimating the glacier-wide MB using the traditional method is risky.”

This could be understood as meaning that the nonlinear model is outperformed by the traditional model, whereas the intended meaning is opposite. Suggest to change to:

The better performance of the nonlinear model...

Done.

L536

(2023/23_2020) --> (2022/23_2020)

Done.

L583

hence. --> hence,

Done.