# Annual to seasonal glacier mass balance in High Mountain Asia derived from Pléiades stereo images: examples from the Pamir and the Tibetan Plateau (tc-2022-264)

**By Daniel Falaschi et al.**

Reply to anonymous referee#2

**Specific comments:**

**Belart et al.,2017 states that the bulk snow density is most likely the largest contributor to uncertainty in winter geodetic mass balance. In the chapter "3.1.5 Bulk density" in the manuscript, the authors refer to other studies and assumes uncertainty values, e.g. that the density values referred to are from snow pits. It is limited data of snow density in the study regions. The authors should discuss this uncertainty more and be clearer on the consequences it might have for the results.**

Thank you for the comment. It is indeed unfortunate that no further in situ densities are available to us for the selected study sites. In these conditions, we have investigated the possible effects and in section 5.1.1 of the discussion, we elaborate on the so-called triangulation tests, which illustrate the varying mass balance values when using different material densities. We provide results for two types of tests.

A first test evaluates differences in mass balance as retrieved from the accumulated (total hydrological year) vs. the sum of individual (seasonal) survey periods in the 2022 hydrological year. We illustrate the variability in mass balance residuals on both glacier-wide and glacier specific scale. This test provides confirmation of the findings of Pelto et al. (2019), in that the distribution of glacier surface classes is actually more important that assumed densities.

In the second triangulation test, we elaborate on the influence of varying material density further, and evaluate the accumulated 2020-2022 mass budget vs the sum of all the individual annual periods in two possible scenarios following Huss, 2013: a) a density of 850 ±60 kgm$^{-3}$ and b) a 3-year weighted density (Muztag Ata = 774 ±60 kg m$^{-3}$). Our results agree in fact with those of Huss et al. (2013), and confirm that using period-weighted densities reduces the differences between the accumulated vs. added mass budgets.

In addition to the above, we will expand the discussion taking into account the findings of Pelto et al. (2019) regarding how the variability of field surveyed densities in comparison with assumed densities can affect glacier mass balance.

**The use of the surface classification of snow, ice and firn from Sentinel-2 can be clarified in chapter "3.1.2 Classification of snow and ice using Sentinel-2 scenes". The chapter gives a good description of how the analysis is done, but it can be elaborated in the start of the chapter what use these data has for the geodetic glacier mass balance and why it is important.**

We will add a brief sentence about the use of the surface classification maps in the geodetic method, so as not to repeat methodological details later found in section 3.1.2. we will expand on the relevance and consequences of the snow and ice distribution as requested.

**Some of the sentences and text includes to many parentheses with additional information or clarifications. A suggestion is to go through the whole manuscript text in general and write shorter sentences that are clearer and easier to read. Here is an example to illustrate: L: 595: "Overall, we find the glacier-wide and (for the most part) individual differences to be well within the uncertainty ranges, and attribute the differences to the overall small differences in average density (which in turn derives from the snow and ice distribution) of the September 2021 (590 kg m-3) and April 2022**

**Sentinel-2 (630 kg m-3) snow and ice masks.". The parentheses are sometimes randomly placed, e.g., "(630 kg m-3)" should maybe be placed after "April 2022"?**

We appreciate the reviewer's concern for overall clarity and reading fluidity of the manuscript. As suggested, we will go throughout the manuscript and make a conscious effort to remove unnecessary or redundant parenthesis and brackets, and split long sentences into shorter ones for improved reading. Among the amends, we will include the specific lines indicated by the reviewer above.

**The authors give a good overview of how they used the Glacier Index of Huang et al. (2022), to find glacier accumulation regimes. However, it is no error estimations of the retrieval of firn and wet snow areas from the remote sensing data, and this should be elaborated.**

We thank the reviewer for this suggestion. We will include a new paragraph on the error assessment and correction. Citing the supplementary material of Huang et al. (2022), *"…the firn area ratio can be overestimated for two surface types: (1) debris covered by very thin snow which may be taken as clean ice/snow on optical satellite image, but the snow can be penetrated by SAR; (2) ice crevasses, which may form a corner reflector effect to the SAR satellite. Both cases will cause high SAR backscatter coefficients regardless of the season, and lead to misclassification as firn instead of debris and ice. To account for these effects, we assume that the pixels higher than -6 dB on both winter and late summer SAR images are misclassified as firn, and the pixels that are lower than -14 dB on both winter and summer SAR images are misclassified as wet snow pixels, and correct these the surface type accordingly."* We will rewrite this information in the manuscript but still refer to the supplementary material for full details.

**Technical comments:**

**L: 91: "The major aims of this paper are therefore to investigate the potential and limitations of geodetic mass balance estimates derived from VHR Pleiades satellite data (using 5 DEMs over the 3-year period 2020-2022)." Should it be data between 2019 and 2022? (Ref. table 1).**

Whilst we reckon that our earliest dataset stem from 2019, in the study we actually assess the geodetic mass balance of three hydrological years (2020, 2021 and 2022). The hydrological year 2020 starts in 2019, so this issue is a bit tricky. We will change to geodetic mass balance between 2019 and 2022, but will clarify the issue with the hydrological year in the text.

**L:425-429: "To account for different glacier areas between the study sites, we express firn and wet snow areas on each region as a fraction of the total glacier area (hereafter referred to as firn area ratio and wet snow area ratio). This ratio can vary to a great extent across different geographic regions through time, whilst interannual variations of the firn area ratio remain relatively small." Which ratio do the authors refer to when compared to the firn area ratio? Glacier index, I? A suggestion to rewrite sentences.**

Many thanks for the observation. Here we simply compare the interannual variability of the wet snow area ratio and the firn area ratio. We will amend this for clarification.

**L: 440: "First, the Landsat scenes are used to recognize debris-covered and debris-free areas (ice and snow) on glaciers surface applying a threshold to the previously computed Normalized Difference Snow Index [NDSI] (Bruns et al., 2014).". The authors describe the use of Landsat-data for glacier higher spatial resolution?**

This is a valid question. In principle, Sentinel-2 scenes would also be a good choice to identify debris-covered and debris-free areas on glaciers. On Google Earth Engine, the highest resolution of the Sentinel-1 SAR images is 10 m. However, in the methodology developed by Huang et al. (2022), the spatial resolution of the Sentinel-1 scenes is resampled to 30 m to reduce the speckle effect on SAR images, which may affect the firn and snow identification. The method thus uses 30 m resolution Landsat images, matching the resampled SAR images, to identify and remove debris.

**L: 830: "The ever increasing and availability of very-high resolution optical satellites (with stereo capability and relatively short revisit time) will allow for increasing the number of glaciers in isolated regions that can be readily monitored.". Can the authors clarify which satellite sensors they are referring to in the last sentence of the conclusion? It is not planned many optical missions with stereo capability in the future. Consider to be more specific and give examples of missions you refer to.**

Good point. We will add a brief list of VHR satellites with stereo capability (Pleiades, WorldView 1-2, SPOT6-7) that are currently operating, whilst we also listed ALOS-3, which was recently launched. We will also remove the "ever increasing" statement in the text.

**L: 1015: Wrong year in Huang et al., 2022 in reference list.**

Many thanks for noting this typo. We will amend this accordingly.

**Figure 1: It is not clear to me which glaciers are "investigated glacier" in the figures. Is it all of them? Consider changing color or outline and rewrite to "investigated glaciers".**

We will thicken the glacier outlines and reduce their transparency for a better visualization. We will also eliminate duplicated coordinates and increase the size of the grid labels in this figure.

**Figure 4 and 6: Cannot really see the dh variation in the figures. A suggestion is to make the figures larger, and subsets of the individual glaciers discussed in the text can also be included.**

**Figure 8: Improve the representation and better the resolution of the plots.**

**Figure 9: It is hard to see the difference between the lines indication "this study" in the plots. Consider changing color on either "annual time step" or the individual glaciers.**

Many thanks for the suggestion. We will modify all figures by using thicker lines, different line types to separate our results from previous studies, a color-blind friendly palette, increased font size and larger scales when possible. In Figures 4 and 6 we will incorporate hillshade images as background on all panels, to better illustrate the relation between the glacier elevation changes and topography.

**References cited in this reply:**


Huang, L., Hock, R., Li, X., Bolch, T., Yang, K., Wang, N., Yao, T., Zhou, J., Dou, C., & Li, Z. (2022). Winter accumulation drives the spatial variations in glacier mass balance in High Mountain Asia. Science Bulletin, S2095927322003644. https://doi.org/10.1016/j.scib.2022.08.019

Huss, M., Sold, L., Hoelzle, M., Stokvis, M., Salzmann, N., Farinotti, D., & Zemp, M. (2013). Towards remote monitoring of sub-seasonal glacier mass balance. Annals of Glaciology, 54(63), 75–83. https://doi.org/10.3189/2013AoG63A427

Pelto, B. M., Menounos, B., & Marshall, S. J. (2019). Multi-year evaluation of airborne geodetic surveys to estimate seasonal mass balance, Columbia and Rocky Mountains, Canada. *The Cryosphere*, *13*(6), 1709–1727. https://doi.org/10.5194/tc-13-1709-2019