Reviewer 2

The manuscript presents an interesting and well-documented analysis of extreme snow accumulation on an avalanche cone using time-lapse and UAV photogrammetry. The overall concept — estimating intense avalanche-driven accumulation — is highly valuable, and the transparent description of the SfM workflow is a clear strength. This is a valuable contribution, and the study has clear potential for publication after addressing several minor to major points outlined below.

We would like to thank Reviewer 2 for their comments which we have carefully addressed.

Main comments:

1. The study would benefit from placing the results in a broader mass-balance context: The central limitation of the manuscript is that it does not quantify the relative contribution of avalanche-derived accumulation to the glacier-wide mass balance. Although the authors show exceptionally high local mass gain (up to +23 m w.e.) and briefly compare it to GLACIOCLIM reference stakes, the comparison remains qualitative. Because the area of the cone and the mean accumulation across the glacier's accumulation zone are known, a simple scaling analysis could reveal whether the cone represents a negligible local anomaly or a meaningful component of the glacier's annual mass budget. Without this quantification, the broader significance of the findings remains unclear. An alternative and complementary approach could be a process-based glacier mass-balance model that explicitly accounts for snow-redistribution processes, which would help quantify how avalanche input modifies the glacier's overall accumulation regime.

As suggested, we have estimated the importance of avalanching at this particular location relative to the mean accumulation across the entire accumulation area, based on the extrapolation from the stake measurements. This has been added at the end of section 4.3.3 (L396-402):

'When integrated across the entire survey domain, the cone-wide mass balance was 2.3 +/- 2.3 m w.e. for 2023/24 and 2.7 +/- 2.4 m w.e. in 2024/25. In contrast, the four GLACIOCLIM accumulation stakes - located between 2890 and 2980 m a.s.l. in non-avalanche-fed areas - recorded average annual balances of 0.3 +/- 0.1 m w.e. for the hydrological year 2023 and 0.8 +/- 0.4 m w.e. in 2024. In comparison, the annual mass balance was 49 +/- 16 times higher on the top of the cone, 9 +/- 5 times higher in the lower extents, and 6 +/- 4 times higher for the cone as a whole. As a result, while the cone represented only 1.7% of the accumulation zone of Argentière, it contributed 6.8 +/- 6.4 % of the total accumulation when compared to the spatially interpolated stake measurements in the accumulation zone.'

We have also referred to these numbers in the discussion (section 5.3, L512-517):

'These avalanche cones act as accumulation "hotspots", with this particular cone contributing 6.8 +/- 6.4 % of the total accumulation for only 1.7% of the accumulation area, so an accumulation enhancement factor of 4.0 +/- 3.8. On a glacier of Argentière's scale, these cones represent a secondary contribution compared to main-trunk accumulation (Kneib et al., 2024b), however for smaller mountain glaciers, this mechanism becomes the primary driver of mass turnover (Purdie et al., 2015; Mott et al., 2019; Kneib et al., 2025).'

In this Section 5.3, we also discussed the comparison with a mass balance model that accounts for snow redistribution by avalanching, published by Kneib et al. (2024) (L505-512):

'Our measurements provide a high-resolution benchmark for regional models. For instance, the SnowSlide parameterization of gravitational snow redistribution by avalanches estimated an additional accumulation of 1.5 +/- 0.4 m w.e. yr^{-1} for the cone over the period 2012–2021, with some local values reaching 3.9 +/- 0.4 m w.e. yr^{-1} (Kneib et al., 2024b). This is significantly lower than our observed values of 23 +/- 4 m w.e. in 2023 and 16 +/- 4 m w.e. in 2024, but aligned with the cone-wide mass balance of 2.3 +/- 2.3 m w.e. for 2023/24 and 2.7 +/- 2.4 m w.e. in 2024/25, relative to the annual mass balance measured in the accumulation zone outside of the cone (0.3 +/- 0.1 m w.e. in 2023 and 0.8 +/- 0.4 m w.e. in 2024). This validates the overall mass redistribution predicted by SnowSlide, despite the fact that it misses the extreme accumulation values, likely due to the coarse resolution of the DEM used (30 m, Kneib et al., 2024b). '

2. A central strength of the manuscript is the transparent description of the time-lapse SfM workflow and the careful comparison with UAV-derived elevation changes. However, several methodological aspects related to reconstruction quality and uncertainty quantification would benefit from deeper analysis and clearer discussion. First, while the manuscript clearly demonstrates a systematic underestimation in the time-lapse SfM (2–3.3 m), the potential causes of this bias are not yet adequately discussed. Factors such as the strongly off-nadir viewing geometry, long camera–object distance, etc could plausibly contribute. A brief reflection on these aspects, supported by established SfM literature (e.g. James et al., 2019; Smith et al., 2020), would help contextualize the observed bias. Second, the treatment of uncertainties in the submergence velocity could be expanded. In particular, the temporal variability of near-surface density, the assumption of constant Vsub, and the propagation of DEM uncertainties merit a more explicit discussion. Particularly, the manuscript assumes a temporally constant submergence velocity retrieved from summer Vsub. It may be worth considering whether this assumption holds throughout the year, given that processes such as snow loading, firn compaction, meltwater percolation, and seasonal changes in ice-flow dynamics could influence vertical strain rates. A brief reflection on whether such seasonal effects might be relevant in this setting could help clarify the associated uncertainties. Third, the manuscript notes seasonal differences in SfM performance but does not explore them further. Given the two-year dataset, even a concise assessment of seasonal influences—illumination, snow surface conditions, camera stability—using simple metrics (e.g. point density or reprojection error) would enhance methodological transparency.

   Addressing these points would further clarify the limitations and strengths of the time-lapse photogrammetry and the derived submergence-velocity estimates.

Thanks for the detailed suggestions that we have addressed as follows:

1. We have expanded the discussion on the systematic biases observed, which are indeed likely related to the strongly off-nadir geometry. The James et al. (2019) or the Smith et al. (2020) publications are not findable but we have referred to Wackrow and Chandler (2011) (L422-423):

‘This underestimation is likely due to the different viewing angles of the time-lapse cameras, which are strongly off-nadir relative to the UAV (e.g. Wackrow and Chandler, 2011).’

2. We appreciate the concerns related to the assumptions underlying the submergence velocities. Note that we had already covered these aspects extensively in the last paragraphs of Section 5.1, and we are thus unsure which elements of discussions are deemed to be missing. The corresponding discussion reads (L449-469):

   ‘Beyond density, our derivation of surface mass balance relies on two fundamental assumptions regarding the submergence velocity: the spatial homogeneity of summer ablation and the temporal consistency of Vsub over seasonal scales. While the loss of the stakes located on the upper part of the cone limited our ability to directly measure ablation at the top of the cone, we justify our extrapolation of a uniform mass balance in summer 2023 based on three factors. First, distributed energy-balance modelling by Roussel et al. (2025) indicates consistent incoming shortwave radiation and ablation rates in this specific area. Second, our time-lapse data confirmed the absence of major avalanche events during the 2023 calibration period (Fig. 9b). Third, when comparing summer 2023 and 2024 data in regions unaffected by late-season avalanches, we observed consistent Vsub values (Fig. 8).

   The assumption of a temporally constant Vsub remains a significant simplification. Our observational framework does not fully constrain the temporal variability of submergence in a setting characterized by rapid thickness fluctuations, which likely drive temporal changes in both driving stresses and compaction rates - potentially affecting even the near-surface snow layers during the ablation season. These uncertainties are likely most pronounced at the top of the cone, where thickness changes are maximized and logistical constraints precluded in situ measurements. While the stationarity of ice flow and surface slopes is well-documented in non-avalanche-fed accumulation zones (Stocker-Waldhuber et al., 2019; Vincent et al., 2020), including in the Argentière basin (Kneib et al., 2024b), such assumptions are more difficult to validate in our avalanche-fed system. We note that because our calibration period for Vsub encompassed the full range of annual cone elevations, these transient effects are likely at least partly integrated into our estimated uncertainty range, and despite these limitations, our derived maps offer a critical refinement of the spatially smoothed flux inversions from remote sensing studies (Kneib et al., 2024b). Future investigations into these dynamic adjustments are recommended, though the logistical challenges of monitoring such high-relief environments remain considerable.’

   We remain open for more concrete suggestions on how this discussion can be expanded.

3. As suggested we have added a figure to the supplementary (Fig. S6) where we plotted both the total number of points, the absolute median and the Normalized Median Absolute Deviation (NMAD) of the M3C2 distance over stable terrain to indicate the evolution of the uncertainties from the Structure-from-Motion photogrammetry with time and identify potential controls.

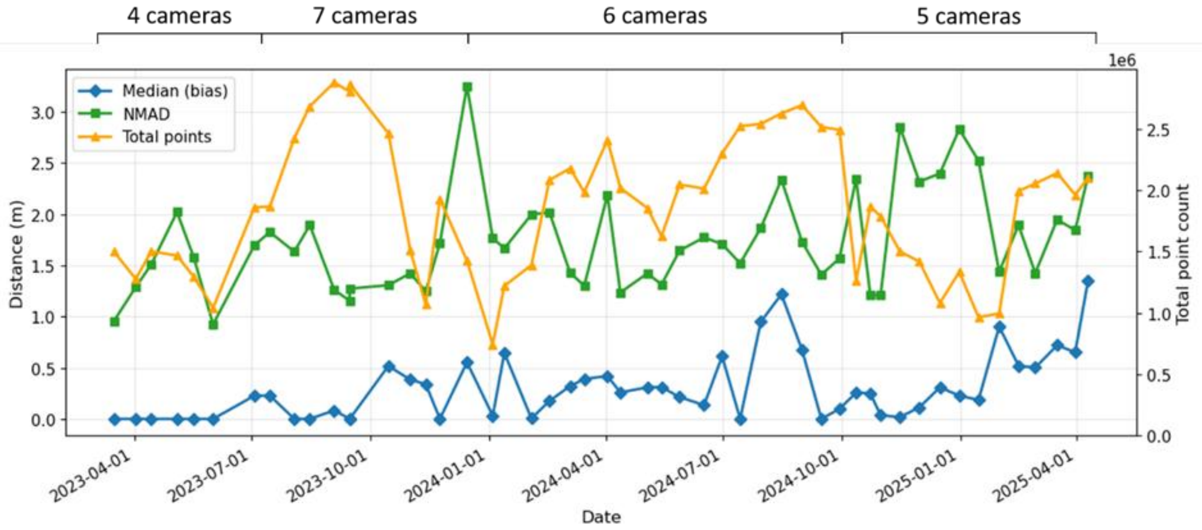


Figure S6: Absolute median (bias) and Normalized Median Absolute Deviation (NMAD) of the M3C2 distance over stable terrain relative to the 27 September 2023 reference point cloud, and total number of points of the point clouds as a function of time. The segments above the plot indicate the number of cameras available for the time-lapse photogrammetry.

We added a description of the experiment, the results and interpretation in the different relevant sections:

L175-179: 'Third, we computed the evolution of the absolute median (bias) and Normalized Median Absolute Deviation (NMAD) of the M3C2 distances over stable terrain relative to the 27 September 2023 reference point cloud. This third experiment allowed us to isolate the influence of seasonality and varying illumination on the photogrammetric reconstruction.'

L279-283: 'For our setup there were at least 4 cameras available for the whole duration of the survey, so the strongest influence on the number of points and on the bias and precision came from the seasonality (Fig. S6). Indeed, the November-February months had a relatively high bias (0.31 m on average) and NMAD (2.0 m) of M3C2 distances over stable terrain, compared to the March-October months, with bias and NMAD of 0.29 m and 1.6 m, respectively. Similarly, the mean number of points was lower during these winter months (1.4 million) compared to the rest of the year (2.1 million).'

L433-439: 'However, for our setup there were at least 4 time-lapse cameras available during the whole duration of the study period, which meant that the strongest influence on the point cloud precision, bias and number of points came from the seasonality, with less points and higher uncertainties in the winter months (November-February) with low light conditions, extensive shading and smooth snow surfaces (Fig. S6). Nonetheless, the seasonal effect on the uncertainties remained limited with a 25% increase in NMAD and 7% increase in bias on average during the winter months (Fig. S6). Ultimately, the high frequency of data acquisition provided *useful insights into the timing of mass distribution that would be impossible to capture via traditional UAV or LiDAR surveys.'*

Specific comments:

1. Further studies should be mentioned when discussing snow depositions on glaciers such as Dadic et al., 2010: Dadic, R., Mott, R., Lehning, M., & Burlando, P. (2010). Wind influence on snow depth distribution and accumulation over glaciers. *Journal of Geophysical Research: Earth Surface*, *115*, F01012 (8 pp.). https://doi.org/10.1029/2009JF001261.

We have added this reference to the introduction (L30-31): 'Glaciers gain mass primarily through solid precipitation and snow redistribution processes such as wind drift and avalanching (Dadic et al., 2010; Laha et al., 2017; Brun et al., 2019).'

2. The SfM workflow is described transparently, but key references on off-nadir photogrammetry and systematic SfM biases are missing. Given the ~1 km camera–object distance and strongly oblique viewing geometry are well-known sources of negative elevation bias. A short discussion of these mechanisms would help explain the observed 2–3.3 m underestimation in the time-lapse DEMs.

Agreed. Please see our response to general comment n°2.

3. The manuscript shows that the avalanche cone experiences exceptionally high mass gain, but the glacier-wide significance remains unclear. A quantitative comparison between the cone's annual mass balance (up to +23 m w.e.) and the glacier-wide accumulation would greatly strengthen the interpretation. Because the authors know both the cone area and the mean accumulation across the glacier's accumulation zone, a simple scaling analysis could reveal whether the cone contributes a negligible or substantial share of the total annual mass input.

   For instance, even though the cone represents only a very small fraction of the total accumulation area, its annual mass gain is an order of magnitude higher than typical accumulation elsewhere on the glacier. This means that the cone could contribute a non-negligible share of the glacier's total annual accumulation, despite its limited spatial extent. Highlighting this contrast would help clarify whether the cone is merely a local anomaly or a meaningful component of the glacier's overall mass budget. Integrating this perspective would strengthen the interpretation of the mass-balance implications presented in the manuscript.

This is an excellent suggestion, which we have added to the manuscript. See detailed response to general comment n°1.

4. The manuscript presents clear evidence that avalanches, wind redistribution, and storm characteristics exert a dominant control on the spatial pattern of accumulation at the cone. Against this background, it remains unclear why the study does not

explore snow-redistribution modelling, even at a simplified level. Given the pronounced influence of these processes, a process-based or reduced-complexity simulation — for example using established snow-transport models or simple avalanche-runout schemes — could have provided valuable context for interpreting the observed mass gain and its sensitivity to meteorological forcing and topographic controls.

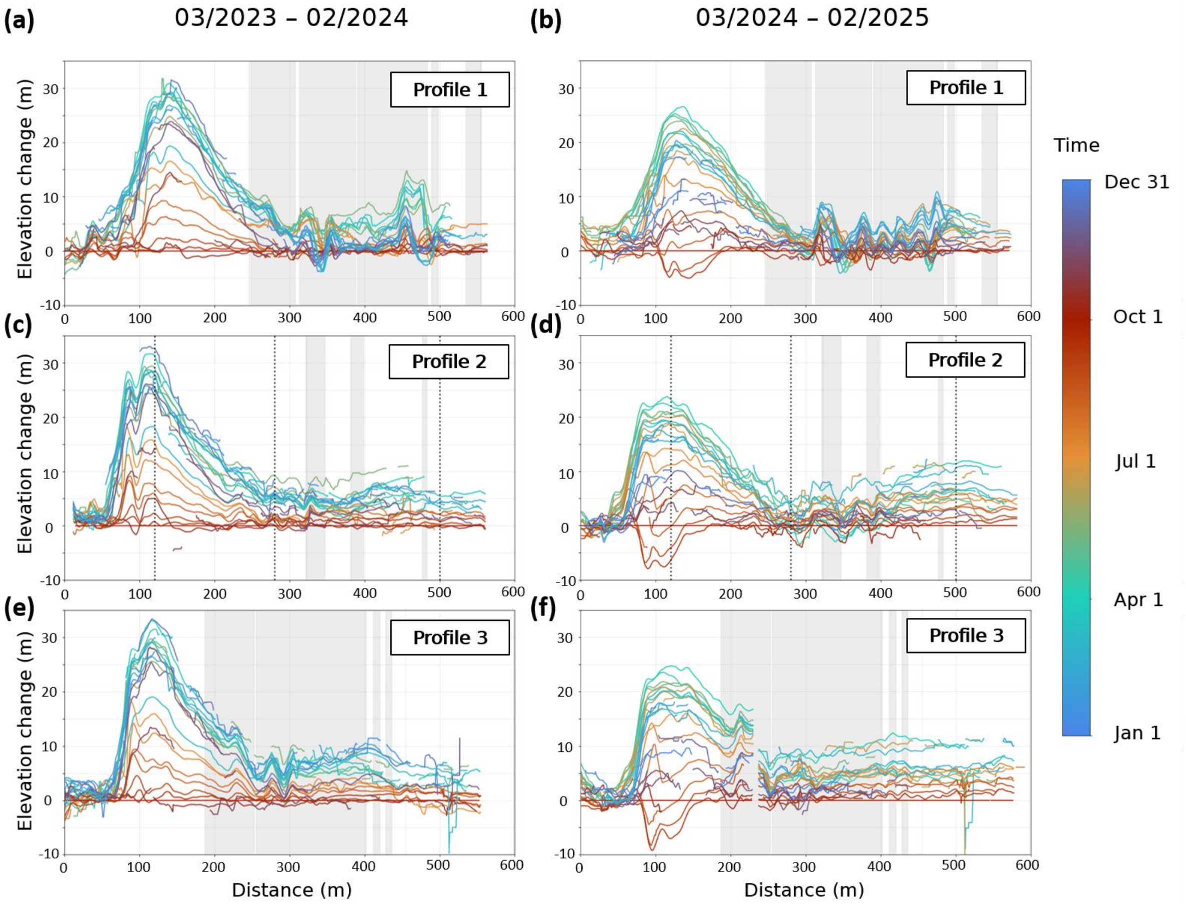
Because the cone represents a highly constrained and well-defined deposition environment, it would also serve as an interesting test case for such modelling approaches. Even if a full modelling framework lies beyond the intended scope of the study, a brief explanation of why no snow-redistribution simulations were attempted would improve transparency and help readers understand the limits of the current interpretation.

In the discussion, we directly compared our results with those of a glacier mass balance model which accounts for avalanching based on a parametrization (Kneib et al., 2024). As detailed in our response to general comment n°1, we have expanded on this comparison to make this clearer.

5. Several of the figures in the Results section are informative, but their interpretability could be improved. At present, many different panels require substantial effort from the reader to understand what is being shown and how the different datasets relate to each other. This is particularly relevant because the study relies heavily on spatial patterns and temporal changes, which depend on clear visual communication.

   Font types and sizes differ not only between figures but sometimes even within the same multi-panel figure. This gives the visual presentation a fragmented appearance and makes it harder to read labels, legends, and axes consistently. Harmonising font style and size across all figures would significantly improve clarity.

Agreed, we have homogenised the font sizes and types between figures, which led us to update figures 5, 7 and 9. More specifically, for figure 5 we have added the x-axis title, which corresponds to a distance (in meters), as well as the title of the colorbar (Time). We have also increased the font size of the different elements of this figure.


(a)
03/2023 – 02/2024
(b)
03/2024 – 02/2025
Profile 1
Profile 1
(c)
(d)
Profile 2
Profile 2
(e)
(f)
Profile 3
Profile 3
Elevation change (m)
Distance (m)
-10
0
10
20
30
0
100
200
300
400
500
600
Time
Dec 31
Oct 1
Jul 1
Apr 1
Jan 1