

Response Letter

Dear Editor Ruth Mottram and Reviewers,

Thanks for handling and review our manuscript (EGUSPHERE-2026-2150). We have carefully carried out a major revision to improve our manuscript based on comments from two anonymous reviewers. The major revision includes following key enhancements:

1. **We quantified the uncertainties on SMB estimates.** We calculated standard error metric. We further quantified the uncertainties using 100,000 Monte Carlo simulations.
2. **We strengthened the contextualization of the Dome A SMB** through comparison with independent observations from Dome A and other Antarctic Plateau sites.
3. **We clarified the treatment of observation data, ERA5 forcing, and surface vapor exchange,** including quantification of missing stake and AWS records, specification of gap filling, location of ERA5 point, and the interpretation of latent heat flux.

We hope our revision adequately addresses the concerns raised by the reviewers and that the revised manuscript meets the standard criteria of TC Journal. Please see below our detailed (blue text) point-by-point response to the reviewers' comments (black text), and any direct quotations from the revised manuscript are underlined.

Thank you very much.

Best regards,

Xiyue Zhang on behalf of co-authors

Chinese Academy of Meteorological Sciences

Reviewer 1:

General Comments

This manuscript presents a substantial modeling effort combining a firm densification model with stake observations to estimate surface mass balance at Dome A. The

methodological work on the firm densification model is thorough. The primary conclusion is that firm densification is a major source of error in stake-derived SMB estimates, which can be addressed by using a firm densification model. The paper's title would suggest a stronger focus on the actual SMB result, thus, I suggest to contextualize the derived SMB value.

Response: We are grateful to the reviewer for your thoughtful review and supportive comments on our work. We agree that the actual SMB result should be emphasized in the manuscript. We, therefore, have strengthened the contextualization of the SMB estimations through comparisons with previous observations at Dome A and other regions. We have carefully revised the manuscript to address all the comments. Please find detailed responses below.

Specific Comments

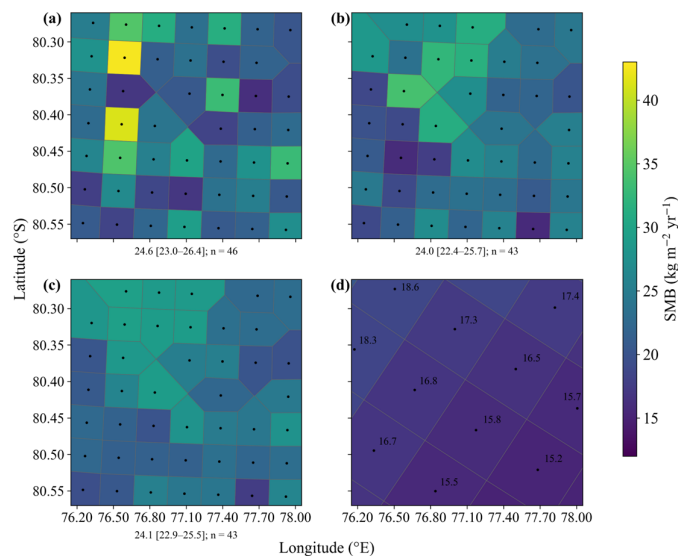
1. While Sect. 3.1–3.2 provide a thorough characterization of the FDM (density profile calibration, column-wide subsidence), the step that most directly supports the paper's title, the subsidence at the stake bottom depth and its use to correct stake-derived SMB (Sect. 3.3), is comparatively brief, and the actual corrected mean SMB values for the two periods (2008–2013 and 2013–2024) are neither explicitly reported anywhere in the text, nor in Fig. 5. Given that these two values are part of the central result implied by the title, I would recommend explicitly stating them (e.g., as annotations and maybe even in Fig. 5), along with an uncertainty range. Since the number of valid stake readings differs between the two periods (and other uncertainties including a mobile stake bottom relative to the surrounding snow layer, strong microrelief around the stake, parallax error arise from the stake method), an uncertainty estimate that reflects these uncertainties would strengthen confidence in these derived SMB values. Additionally, the reported mean SMB of $24.14 \text{ kg m}^{-2} \text{ yr}^{-1}$ is given to two decimal places, implying a high precision. Without a stated uncertainty, this level of precision is difficult to justify.

Response: Thanks for your constructive comments. We have expanded Sect. 3.3 to give the corrected mean SMB values for the periods 2008–2013 and 2013–2024, and these values have been annotated in Fig. 5. As the conventional measure of uncertainty for the mean SMB of the stake array, we calculated the standard error as SE. The corrected mean SMB was $24.6 \pm 0.9 \text{ kg m}^{-2} \text{ yr}^{-1}$ for 2008–2013 based on 46 valid stakes, $24.0 \pm 0.7 \text{ kg m}^{-2} \text{ yr}^{-1}$ for 2013–2024 based on 43 valid stakes, and $24.1 \pm 0.5 \text{ kg m}^{-2} \text{ yr}^{-1}$ for 2008–2024 based on 43 valid stakes. Because the conventional SE does not represent all relevant uncertainty sources, we additionally quantified uncertainty using Monte Carlo simulations.

The compaction for each stake was estimated using Piecewise Cubic Hermite Interpolating Polynomial (PCHIP). The interpolation was based on compaction values simulated by the firm densification model for stake bottom depths of 0.8, 1.0, 1.64, 2.0, 2.5 and 3.0 m (see Fig. A1 below). In each simulation, the parallax error was sampled from a uniform distribution between -1 and +1 cm. Because the 2008 exposed length was used to calculate both the observed height change and the initial stake bottom depth,

the same error value was applied to both calculations. Density uncertainty was estimated from the replicate measurements collected in 2011. The strong microrelief error could not be separated from SMB variability at the stake scale, so microrelief was not quantified as an independent source of uncertainty. Microrelief variability was already carried into the distribution of stake array through the spatial block bootstrap. The bamboo stakes are light and have a similar density to snow, so penetration is expected to be negligible (Takahashi and Kameda, 2007). Eisen et al. (2008) noted that light weight stakes satisfy the assumption of stake bottom to the surrounding snow layer to a first approximation. Although small motion cannot be completely excluded, its effect is expected to be limited and was not treated as an independent uncertainty source in the Monte Carlo analyze.

The resulting 95 % uncertainty intervals for the SMB were 23.0–26.4 $\text{kg m}^{-2}\text{yr}^{-1}$ for 2008–2013, 22.4–25.7 $\text{kg m}^{-2}\text{yr}^{-1}$ for 2013–2024 and 22.9–25.5 $\text{kg m}^{-2}\text{yr}^{-1}$ for 2008–2024. A detailed description of the Monte Carlo has been added in Sect. 2.4.3 (page 8, lines 216–229). We have also revised all SMB estimates to one decimal place throughout the manuscript and figures. The corrected SMB values, their uncertainty intervals, and the number of valid stakes in each period have been added to Sect. 3.3 (page 12, lines 305–327), Fig. 5 (page 15, lines 354–363), and Figure A1 and A2 (page 21, lines 527–538).



“Figure 5. Spatial distribution of mean annual SMB at Dome A. (a)–(c) show SMB derived from stake observations after correction for 2008–2013, 2013–2024 and 2008–2024, respectively. The mean SMB is 24.6, 24.0 and 24.1 $\text{kg m}^{-2}\text{yr}^{-1}$. The standard errors (SE) are 0.9, 0.7 and 0.5 $\text{kg m}^{-2}\text{yr}^{-1}$, based on 46, 43 and 43 valid stakes. The Monte Carlo 95 % uncertainty intervals are 23.0–26.4, 22.4–25.7 and 22.9–25.5 $\text{kg m}^{-2}\text{yr}^{-1}$, respectively. (d) Mean annual SMB from 2008 to 2024 simulated by the RACMO2.4p1 model. Black dots indicate stake locations in (a)–(c) and RACMO grids in (d). Some stake observations are unavailable for certain periods, resulting in differences in the number and spatial distribution of valid stakes among panels (a)–(c). These differences cause the interpolation patterns.”

Appendix A

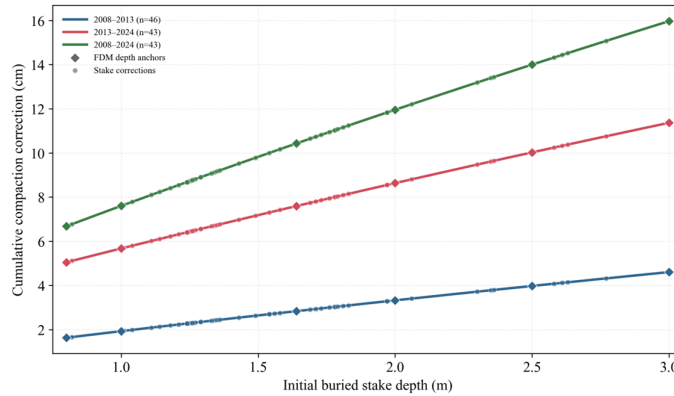


Figure A1. Cumulative correction for firm densification on the initial depth of the stake bottom. The blue, red and green lines show the corrections for 2008–2013, 2013–2024, and 2008–2024 using PCHIP through firm densification simulations at depths of 0.8, 1.0, 1.64, 2.0, 2.5 and 3.0 m. The diamonds mark these six model anchors. The circles show corrections about individual stakes according to the depths inferred from the 2008 stakes readings. The value of n indicates the number of valid stakes in each period.

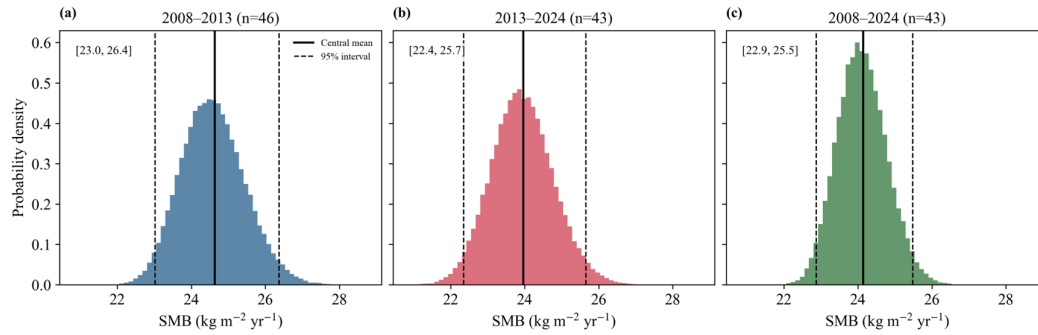


Figure A2. Monte Carlo distribution of SMB after correction. (a)-(c) show the probability density for 2008–2013, 2013–2024, and 2008–2024 derived from 100,000 Monte Carlo simulations. The solid vertical black lines indicate the estimates using the stake bottom of 1.64 m. the dashed vertical lines indicate the 2.5th and 97.5th percentiles of each distribution and the values in brackets give the corresponding 95 % uncertainty intervals. The simulations using a 2×2 toroidal bootstrap, combined stake parallax error, uncertainty in snow density, and difference among stakes in initial bottom depths.”

2. The discussion of the mean SMB value of $24.14 \text{ kg m}^{-2} \text{ yr}^{-1}$ would benefit from contextualizing against independent observations beyond the RACMO comparison, either from Dome A itself or other regional studies from different sources.

Response: We have added a new section 4.2 to Discussion and Figure B1 comparing the Dome A SMB estimate obtained in this study with other estimates from Dome A, Dome C, Dome Fuji, and Vostok. These estimates were derived from snow pits, firn/ice cores, radar, and stake arrays. The modification are as follows:

(1) Sect. 4.2 (page 18-19, lines 447-460):

“4.2 Comparison with independent SMB estimates

In addition to comparison with RACMO, we compare the mean annual SMB of $24.1 \text{ kg m}^{-2}\text{yr}^{-1}$ for 2008–2024 with other observational sources and regions (Fig. B1). Beyond Dome A, the comparison includes results from Dome C, Dome Fuji and Vostok based on snow pits, firn/ice cores, radar measurements, and stake arrays. At Dome A, Hou et al. (2007) and Wang et al. (2013) used a β radioactivity horizon in snow pit to derive a mean accumulation rate of $23.0 \text{ kg m}^{-2}\text{yr}^{-1}$ for 1966–2004 and $21.0 \text{ kg m}^{-2}\text{yr}^{-1}$ for 1965–2009. The estimates from this study is close to the two snow pits estimates.

At Dome C, estimates from a firn core and a stake farm are 28.3 ± 2.4 and $27.2 \pm 0.6 \text{ kg m}^{-2}\text{yr}^{-1}$ (Frezzotti et al., 2005; Stefanini et al., 2025). At Dome Fuji, estimates from a snow pit, firn core, GPR, and stake farms are 25.6 ± 1.7 , 25.5 ± 0.3 , 24.5 ± 0.7 , and $27.3 \pm 1.5 \text{ kg m}^{-2}\text{yr}^{-1}$ (Fujita et al., 2011; Igarashi et al., 2011; Kameda et al., 2008). At Vostok, estimates from snow pits or shallow ice cores and from a stake farm are 20.6 ± 0.3 and $22.5 \pm 1.3 \text{ kg m}^{-2}\text{yr}^{-1}$ (Ekaykin et al., 2004, 2023). The SMB at Dome A lies between the lower values reported for Vostok and the higher values reported for Dome C. The differences may reflect regional variations in snow accumulation related to elevation, distance from moisture sources, snow redistribution and sublimation. Observation period, measurement method, and spatial representativeness should also be considered.”

(2) Figure B1 (page 22, lines 539-545):

“Appendix B

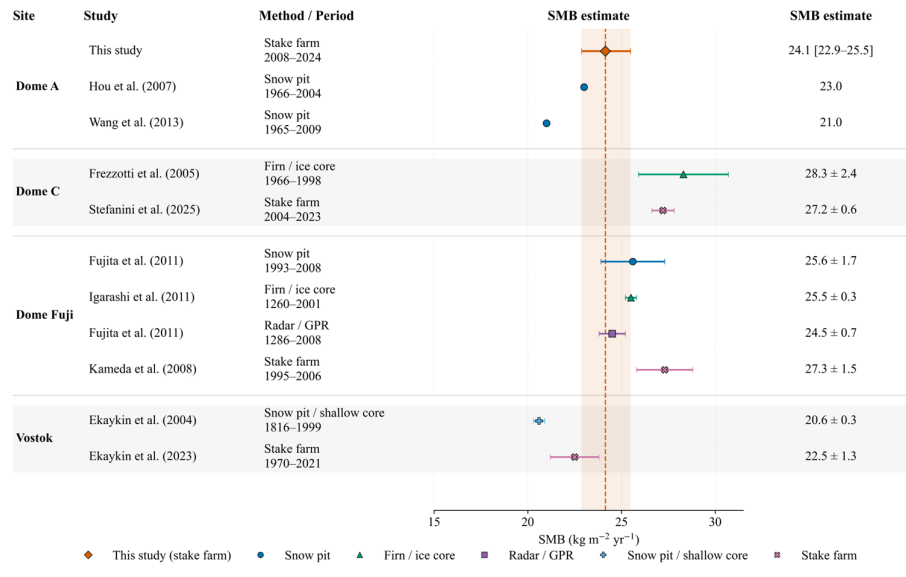


Figure B1. Observations comparison of SMB at Dome A, Dome C, Dome Fuji, and Vostok. The orange diamond and the dashed orange line represents the 2008–2024 Dome A stake array mean annual SMB obtained in this study, with the value of $24.1 \text{ kg m}^{-2}\text{yr}^{-1}$. The horizontal orange bar

and band show its Monte Carlo 95 % uncertainty interval, ranging from 22.9 to 25.5 kg m⁻²yr⁻¹. Published estimates are grouped by site, with the observation method and period. Blue circles, green triangles, purple squares, blue plus, and magenta crosses represent snow pit, firn/ice-core, radar/GPR, snow pit/shallow core, and stake farm estimates, respectively.”

3. Z.61f: This passage remains unspecific in two places. For the Takahashi and Kameda (2007) study: which two methods are being compared? For the Howat (2022) study, please report the percentage rather than (or in addition to) the absolute number, and specify the measured variable: is it SMB, or only height change?

Response: At Dome Fuji, the same stake height change was converted using either the snow density in the upper 0-10 cm, 280 kg m⁻³, or the snow density at the stake bottom depth, 356 kg m⁻³. These approaches yielded SMB estimates of 28.7 kg m⁻²yr⁻¹ and 36.5 kg m⁻²yr⁻¹, respectively. The use of the density at the stake bottom depth increased the estimated SMB by 27 % compared with the surface (Takahashi and Kameda, 2007). At Summit Camp, the value of 15.12 cm a⁻¹ represents a correction to snow depth change caused by compaction, rather than a direct measurement of SMB. Using the snow density of 0.3 g cm⁻³ in that study, this height correction is equivalent to 45.4 mm w.e. yr⁻¹, accounting for 18.5 % of the corrected annual accumulation of 244.8 mm w.e. yr⁻¹. The corrected accumulation is therefore 22.8 % higher than the uncorrected stake network estimate of 199.4 mm w.e. yr⁻¹ (Howat, 2022). We have revised the manuscript (page 2-3, lines 62-71).

4. Z.91: Please add: “X % of stake height records were missing across the study period and were excluded”

Response: 7.7 % of stake height records were missing across the study period and were excluded. We have added information to Sect 2.1.1 (page 4, lines 101-103).

5. Z.99: Please add: “X % of AWS data were missing across the study period”. Additionally, the gap filling method could be specified.

Response: 19.8 % of AWS data were missing across the study period. For all variables except wind speed, short gaps were filled using linear interpolation when the gap were separated by no more than two hours. The wind speed used the mean available observations for each day. The value still missing after these procedures were replaced with the multi-year climatological mean for the corresponding month, day, and hour. The gap filling method has been added to the Sect. 2.1.2 (page 4, lines 114-117).

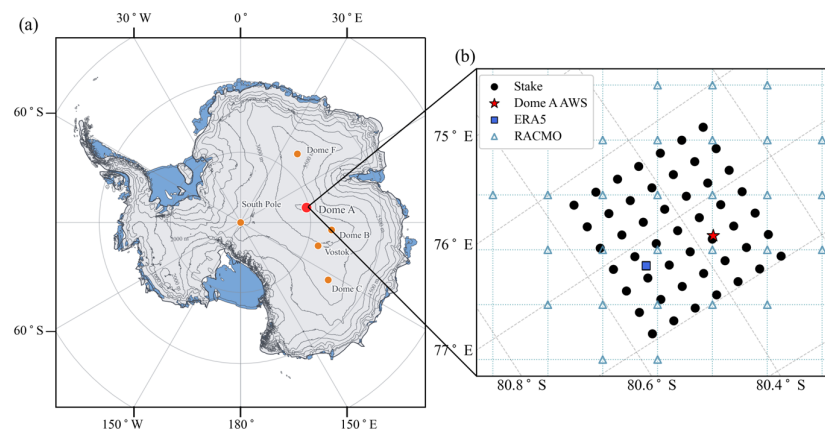
6. Z. 105ff: The final sentence appears to suggest a level of validation for the use of ERA5 at Dome A in firn densification modelling that is not actually supported by the cited references. My suggestion for rephrasing: “ERA5 reproduces the variability of near-surface air temperature reasonably well at Antarctic sites where AWS data are available, and, despite uncertainties in precipitation, provides a continuous and internally consistent climate dataset. We therefore use ERA5 Ts and TP as pragmatic driving fields for our firn densification simulations, acknowledging that a dedicated validation at Dome A and for surface (skin) temperature is still lacking.”

Response: Thanks for pointing this out. We agree and have revised the manuscript. The modification is as follows (page 5, lines 129-131):

“ERA5 reproduces the variability of near-surface air temperature reasonably well at Antarctic sites where AWS data are available, and, despite uncertainties in precipitation, provides a continuous and internally consistent climate dataset. We therefore use ERA5 Ts and TP as pragmatic driving fields for our firn densification simulations.”

7. Fig. 1b) Please mark the ERA5 grid point used.

Response: We have marked the ERA5 grid point in Fig. 1b. The caption has also been revised. The modification is as follows (page 5-6, lines 139-143):



“(b) Enlarged view of the Dome A area, showing the distribution of the stake array (black circles), the Dome A AWS (red star), the ERA5 grid point (blue square), and RACMO grids (blue triangles). The RACMO grids fully cover the spatial extent of the stake array.”

8. Section 2.4.1: Clarification needed for the stake-derived SMB assessment:

- What is the typical stake depth at Dome A: how much protrudes above the surface, and how much is buried? Please also specify the stake material (cf. Eisen et al., 2008, *Reviews of Geophysics*, Ground-based measurements of spatial and temporal variability of snow accumulation in East Antarctica).
- Please clarify already in the Methods that, for the densification correction of stake-derived SMB, only compaction down to the buried stake depth is relevant. This would help clarify that the last two terms of Eq. (1) (V_{ice} , dB/dt) are not merely negligibly small, as currently stated for dB/dt , but structurally irrelevant to the stake-based method regardless of their magnitude, since they describe processes well below the depth range the stake actually integrates over.

Response: For the first question, the stakes used in this study were made of bamboo, with the length of 5 m and a diameter of 2-3 cm. their exposed lengths ranged from 2.23 to 4.18 m, corresponding to insertion depths of 0.82-2.77 m. the mean insertion depth across all stakes was 1.64 m. We have added in Sect. 2.1.1 (page 4, lines 98-99) For the second question, yes, vertical motion below the stake bottom does not affect the stake reading, regardless of the magnitude of V_{ice} and dB/dt . We revised our previous

statement in Sect. 2.4.1 (page 6, lines 166-170) that these two terms could be neglected because of their small magnitudes and clarified that they are irrelevant to the stake-based SMB correction.

9. Z.142: Please be consistent with naming: either use "firn densification vertical velocity" as introduced above, or repeat the variable name V_{fc} here as well.

Response: We have replaced "compaction velocity" with " V_{fc} " for consistency.

10. Z.211ff: Does Fig. 2b show two snapshots (one from 2008, one from 2024) of the modelled density profiles, or the annually averaged density profile? Please also explain the purple line ($\Delta\rho$) in more detail, e.g., that at a given depth z , the same snow layer/isochrone is no longer being compared, since the 2008 and 2024 profiles represent firn of different ages at equivalent depths.

Response: Fig. 2b shows the modelled density profiles at the beginning of 2008 and 2024, rather than annually averaged density profile. The purple line indicates the snow layer located at a certain depth in 2008 moved to a new depth in 2024 after 16 years of compaction, while its density increased by approximately $13\text{--}17\text{ kg m}^{-3}$. The purple line quantifies the increase in density of the snow layers in 2008 by comparing each layer with its corresponding position in 2024. We have revised Sect. 3.1 of the manuscript (page 10, lines 261-269).

11. Z.233ff: "As the snow compacts, the 2008 surface is buried beneath the 2024 surface, while the stake descends with the surrounding snow layers. Consequently, this cumulative subsidence cannot be used for stake correction." Please clarify: this is because the cumulative subsidence applies to the whole column, not to the specific portion of the column that the stake actually "sees."

Response: We acknowledge that this sentence could be ambiguous, so we have revised it. The modification is as follows (page 11, lines 289-292):

"As the snow compacts, the stake descends with the surrounding snow layers. The cumulative subsidence applies to the whole column, not to the specific portion between the surface and the stake bottom of the stake. Consequently, this cumulative subsidence cannot be used for stake correction."

12. Z.256ff: For comparison, you could also provide the corrected SMB value and bias estimate for stake depths of 0.8 m and 3 m.

Response: We have added the corrected SMB values for the 0.8 and 3.0 m sensitivity experiments. The modification is as follows (page 12, lines 323-325):

"For 2008–2024, the depths of 0.8, 1.64, and 3.0 m calculated corrected mean annual SMB of $23.4, 24.1, 25.2\text{ kg m}^{-2}\text{yr}^{-1}$, corresponding to increases of 5.6 %, 8.8%, and 13.4 % relative to the uncorrected SMB ($22.2\text{ kg m}^{-2}\text{yr}^{-1}$)."

13. Z.269f: Did you also density-correct the SMB for the sub-periods 2008-2013 and

2013-2024? If so, please clearly state this. Also, in the caption of Figure 5, it sounds like the values are not density-corrected? This needs to be clarified.

Response: We acknowledge that we previously did not correct the SMB for the sub-periods 2008-2013 and 2013-2024, but we have now done so. We revised the Sect. 3.3 to state this explicitly and also revised the caption of Figure 5. The modification is as follows:

(1) Sect. 3.3 (page 12, lines 317-318):

“The 1.64 m correction increased the SMB from 22.9 to 24.6 kg m⁻²yr⁻¹ for 2008–2013, and from 21.9 to 24.0 kg m⁻²yr⁻¹ for 2013–2024.”

(2) The caption of Figure 5 (page 15, lines 355-356):

“**Figure 1.** Spatial distribution of mean annual SMB at Dome A. **(a)–(c)** show SMB derived from stake observations after correction for 2008–2013, 2013–2024 and 2008–2024, respectively. The mean SMB is 24.6, 24.0 and 24.1 kg m⁻²yr⁻¹.”

14. Figure 5: The diverging colorbar is not appropriate for the strictly positive quantity SMB (cf. Cramer et al., 2020, Nat. Commun., The misuse of colour in science communication). Please use a sequential, perceptually uniform colormap (e.g., viridis) instead. Maybe also explain in the caption, that the missing stakes cause the interpolation patterns.

Response: Thanks for your comments. We have updated the diverging colorbar in Figure 5 to viridis and added an explanation in the caption.

15. Z. 302: Which climatological mean was used to fill gaps, the mean for that specific day-of-year?

Response: Yes, we fill gaps using the multi-year climatological mean for the corresponding month, day, and hour. For example, a missing value at 12:00 on 15 July 2008 was replaced by the multi-year of the available values at 12:00 on 15 July. We have clarified in Sect. 2.1.2 (page 4, lines 116-117) and Sect. 3.5 (page 16, lines 399-400).

16. Z. 305 f: Please note that mm w.e. yr⁻¹ and kg m⁻² yr⁻¹ are numerically equivalent (1 mm w.e. = 1 kg m⁻²). Since both units are used interchangeably throughout the manuscript (e.g., here sublimation/deposition in mm w.e. vs. the reported SMB in kg m⁻²), it would help readability to state this equivalence explicitly once, e.g. in Sect. 2, so readers can follow the arithmetic (e.g., 25.61 – 1.47 = 24.14) without unit-conversion confusion.

Response: We have clarified the numerical equivalence between mm w.e. yr⁻¹ and kg m⁻² yr⁻¹ in Sect. 2.5. The modification is as follows (page 9, lines 243-244):

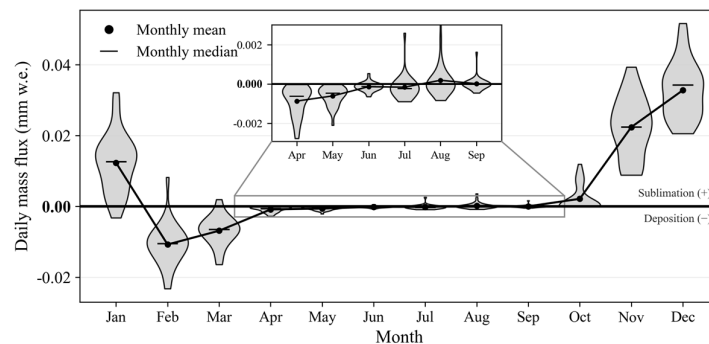
“For water-equivalent mass fluxes, 1 mm w.e. yr⁻¹ is numerically equivalent to 1 kg m⁻²yr⁻¹.”

17. Z.310: This conversion from mass flux to energy flux is not obvious to me: converting the reported net vapor flux ($1.47 \text{ mm w.e. yr}^{-1}$) by multiplying with $L_s = 2.834 \text{ MJ kg}^{-1}$ yields a long-term mean LE of $\sim 0.13 \text{ W m}^{-2}$, roughly an order of magnitude smaller than the stated 'less than 3 W m^{-2} '. Please specify how the value of 3 W m^{-2} was derived.

Response: The value of 3 W m^{-2} was not derived by converting the net vapor flux of $1.47 \text{ mm w.e. yr}^{-1}$. It referred to the approximately upper limit of the summertime climatological daily mean LE reported by Ding et al. (2016). For our results, the net vapor flux of $1.47 \text{ mm w.e. yr}^{-1}$ corresponds to a long-term mean net LE of 0.132 W m^{-2} . And in this study, the maximum climatological daily mean LE is 1.60 W m^{-2} . We have revised the manuscript in Sect. 3.5 (page 17, lines 413-415).

18. Figure 6: Consider adding a thicker/highlighted zero line (0.00 mm w.e.) to make the visual distinction between sublimation and deposition clearer at a glance

Response: We have added a thicker zero line at 0.00 mm w.e. . The modification is as follows (page 17, lines 419):



19. Z.356: “Without applying the scaling factor, the subsidence of 1.64 m snow layer is limited to 0.05 m”: please add for context: 'compared to observed/simulated subsidence on the order of tens of centimeters over the same 2008–2024 period', to make the magnitude of the scaling factors' effect explicit or specify the period.

Response: We have revised Sect. 4.3 to more clearly explain the impact of the scaling factor on the magnitude. The modification is as follows (page 19, lines 475-477):

“Without applying the scaling factor, the subsidence of 1.64 m snow layer is limited to 0.05 m, compared to simulated subsidence on the order of tens of centimeters over the same 2008–2024 period. Consequently, the SMB correction without scaling was approximately 50 % of the correction with scaling.”

20. Inconsistent use of "in situ" vs. "in-situ" throughout the manuscript, please standardize to one spelling and follow the journal guidelines.

Response: All instances have been spelled as “in situ”.

21. Z.91: "in specific period" should be "in a given period" (missing article)

Response: We have revised “in specific period” to “in a given period” as suggested.

22. Z.213: dashed line (instead of dotted)

Response: We have revised “dotted” to “dashed” as suggested.

23. Z.320: Add the plural “s” to “stake observations”

Response: We have revised “stake observation” to “stake observations” as suggested.

24. Z.331: 'Kameda' is named as the sole actor, but two references with different first authors are cited together (Takahashi and Kameda, 2007; Kameda et al., 2008). Maybe consider rephrasing.

Response: We have rephrased this sentence. The modification is as follows (page 18, lines 437-440):

“Takahashi and Kameda (2007) proposed using the snow density at the stake base rather than the surface. Kameda et al. subsequently used the average snow density at the stake base to convert height change to water-equivalent, implicitly accounting for compaction effects via the selection of a representative density”

References:

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