

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 spatial variability and representativeness of the stake observations**, using both the 7×7 stake array and the independent 5×5 stake array to assess kilometer scale variability and the representativeness of individual stake observations.
2. **We strengthened the evaluation of the atmospheric and regional climate models** by adding a comparison between ERA5 and Dome A AWS observations and a grid matched comparison between the stake observations and RACMO2.4p1.
3. **We expanded the evaluation and sensitivity analyze of surface vapor exchange**, including an assessment of the effects of using daily mean wind speed and different treatments of turbulent transfer, with an evaluation of RACMO sublimation.

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

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Reviewer 2:

General Comments

This article presents a refined estimate of the surface mass balance (SMB) at Dome A

on the Antarctic plateau, defined as precipitation minus sublimation in this dry region. The SMB is quantified using a 7×7 array of stakes spaced 5 km apart, covering an area of 30 km by 30 km. A key strength of this article is that it accounts for firn compaction caused by densification, using a densification model calibrated against a locally measured density profile, and that it estimates the contribution of sublimation to the total SMB from an automatic weather station (AWS).

The accurate estimation of the net snow accumulation at Dome A is valuable for evaluating models and improving our understanding of the SMB of the Antarctic plateau. The article is clearly written, and although the methods are standard, they are clearly explained, and the results are well illustrated. However, it seems to me that this article would be better suited to a journal publishing observational data (e.g., ESSD) rather than The Cryosphere, as the scope of the study is limited to Dome A. I leave it to the editor to decide whether this article is well suited to the journal The Cryosphere. Beyond this remark, the article appears scientifically sound and I recommend its publication after the following major and minor comments have been addressed.

Response: We are grateful to the reviewer for their valuable comments and overall positive assessment of our work. We have added quantitative assessment of the spatial variability and uncertainty on each stake's observation, conducted a grid matched comparison between the stake observations and RACMO, evaluated ERA5 against observations from the AWS. Dome A provides a suitable environment for quantitatively assessing the influence of firn densification on stake derived SMB, evaluating the performance of regional climate models and surface vapor exchange in Antarctic interior. We appreciate your support for publication and have carefully revised the manuscript. Please find our detailed responses below.

Specific Comments

1. I recommend adding a discussion of the uncertainty associated with stake measurements: what is the spatial variability of accumulation at the kilometer scale? What is the uncertainty on each stake's observation with respect to the surrounding $5 \text{ km} \times 5 \text{ km}$ area? If no local observations allow this uncertainty to be estimated, I suggest using other existing observations from the Antarctic plateau to estimate it, as this is a crucial point for interpreting the SMB observations.

Response: Thank you for this important suggestion. We have added a quantitative assessment of the spatial variability and uncertainty on each stake's observation. For the 7×7 stake array, the corrected SMB shows spatial standard deviations (SD) of 6.1, 4.3, 3.3 $\text{kg m}^{-2}\text{yr}^{-1}$ for 2008–2013, 2013–2024, 2008–2024, corresponding to coefficients of variation (CV) of 24.8 %, 17.9 %, and 13.7 %, respectively. These values quantify the kilometer scale spatial variability, and the variability is reduced for the longer period.

We used the independent 5×5 stake array covering $100 \times 100 \text{ m}$ at Dome A to evaluate the uncertainty on each stake's observation. For 2008–2013, the SD of this array is 3.6 $\text{kg m}^{-2}\text{yr}^{-1}$, and the CV is 19.1 %. The mean absolute deviation of an individual stake

from local stake array was approximately $2.9 \text{ kg m}^{-2}\text{yr}^{-1}$. Ding et al. (2016), using the same stake array, showed that at least 12 stakes are required to obtain a reliable SMB estimate at the scale of a few hundred square meters, whereas at least 20 stakes are required at the scale of a few tens of square kilometers. We have revised Sect. 3.4.2 of the manuscript (page 15-16, lines 369-377).

2. Section 3.2: I did not understand the purpose of this paragraph. I recommend clarifying it by clearly distinguishing between subsidence due to snow accumulation and subsidence due to sub-surface densification.

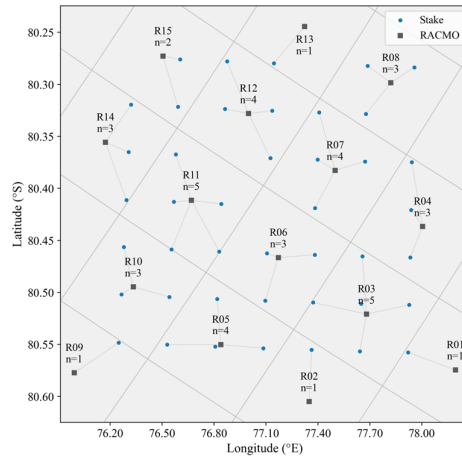
Response: We agree that the original wording did not clearly distinguish these two processes and may cause confusion of the vertical displacement. Snow accumulation adds new mass at the surface and buries existing snow layers. In contrast, firn densification reduces the thickness of existing snow layers. Accumulation can change the overburden stress to influence densification indirectly. The purpose of this paragraph is to quantify the long-term subsidence caused by firn densification over the whole firn column and to provide the necessary context for Sect 3.3. We have revised Sect 3.2 to state this purpose. The modification is as follows (page 11, lines 286-293):

“This value represents the cumulative subsidence of the entire firn column over the same period as the stake observations. It provides a measure of overall magnitude of firn compaction. Figure 3b illustrates the influence of firn densification on snow layer and stake measurements. 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. Only densification between the snow surface and the buried stake bottom affects the relative height recorded by the stake, as quantified in Sect. 3.3.”

3. Section 3.4.2: I feel this section would benefit from more thorough treatment, notably by including the uncertainty on the stake measurements. In addition, L289–292 state that the discrepancy arises because RACMO has a resolution of 11 km: I suggest to aggregate the stake measurements over one or several RACMO grid cells to check whether the larger-scale spatial patterns are well represented in RACMO or not, independently of sub-grid spatial variability.

Response: Thanks for this helpful suggestion. We have added uncertainty on the stake measurements in Sect. 3.4.2. We also performed a grid matched comparison between the stake observations and RACMO2.4p1. Each valid stake was assigned to its corresponding 11 km RACMO grid cell and then stakes within each cell were averaged. 11 grid cells containing at least two valid stakes were included in the comparison. The stake and RACMO fields showed broadly similar northwest to southeast gradient directions. The larger scale spatial patterns are well represented in RACMO and supported by the stake observations. The aggregated stake observations show stronger spatial variability than RACMO, indicating that RACMO produces a smoother SMB spatial field than observed. RACMO SMB remains lower than the aggregated stake

SMB in all 11 grid cells, with differences ranging from 4.8 to 10.9 $\text{kg m}^{-2}\text{yr}^{-1}$. The RACMO underestimation cannot be attributed solely to differences in spatial resolution, but may reflect limitations in the parameterization of local surface processes over Dome A. Two figures have been added to Figure S2 and S3, and Sect 3.4.2 (page 16, lines 378-390) has been revised accordingly. The modification is as follows:



“Figure S2. Spatial matching of the 43 valid stake observations for 2008–2024 to the corresponding 11 km RACMO2.4p1 grid cells over Dome A. Blue circles indicate stake observations, grey squares indicate RACMO grid cell centers and grey lines connect each stake to its corresponding grid center. R01-R15 denote the 15 RACMO grid cells containing stakes, and n gives the number of stakes. Eleven grid cells contain at least two valid stakes and are used for comparison.

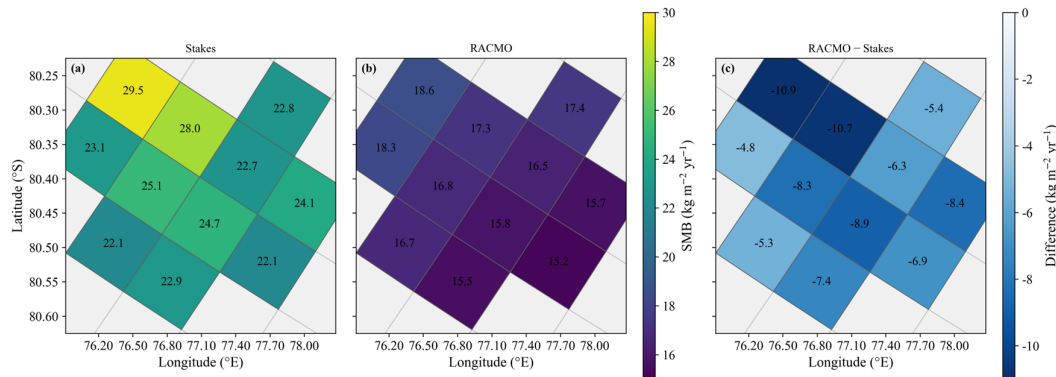


Figure S3. Grid matched comparison of mean SMB between corrected stake observations and RACMO2.4p1 over Dome A for 2008–2024. (a) Mean SMB of valid stake observations within each 11 km RACMO grid cell. (b) RACMO2.4p1 SMB for the same cells. (c) Difference between RACMO2.4p1 and the aggregated stake observations. Only the 11 RACMO grid cells containing at least two valid stakes are included.”

4. I would suggest adjusting the number of significant figures throughout the manuscript. In my view, one decimal place would be sufficient for SMB values (e.g., XX.X $\text{kg m}^{-2}\text{yr}^{-1}$ instead of the current XX.XX $\text{kg m}^{-2}\text{yr}^{-1}$).

Response: Thanks for this recommendation. We have revised the manuscript to report SMB values consistently to one decimal place.

5. Use a consistent unit for SMB throughout the manuscript: $\text{kg m}^{-2} \text{yr}^{-1}$ (the text sometimes uses $\text{m yr}^{-1} \text{w.e.}$, cm a^{-1} , $\text{mm yr}^{-1} \text{w.e.}$)

Response: We have converted all expressed in m w.e. yr^{-1} and cm w.e. yr^{-1} to mm w.e. yr^{-1} , thereby standardizing the water equivalent unit. We have added in Sect. 2.5 (page 9, lines 243-244) that mm w.e. yr^{-1} and $\text{kg m}^{-2} \text{yr}^{-1}$ is numerical equivalence.

6. L35: 131 Gt yr^{-1} for which period?

Response: The reported mass loss rate refers to the period from April 2002 to September 2020. We have added the corresponding period and uncertainty (page 2, lines 36-37).

7. L60–61: How much is 15.1 cm a^{-1} as a percentage of the mean accumulation at Summit?

Response: At Summit Camp, the value of 15.12 cm a^{-1} represents a correction to snow depth change caused by compaction. Using the snow density of 0.3 g cm^{-3} in that study, this height correction is equivalent to $45.4 \text{ mm w.e. yr}^{-1}$, accounting for 18.5 % of the corrected annual accumulation of $244.8 \text{ mm w.e. yr}^{-1}$. The corrected accumulation is therefore 22.8 % higher than the uncorrected stake network estimate of $199.4 \text{ mm w.e. yr}^{-1}$ (Howat, 2022). We have revised the manuscript (page 3, lines 67-71).

8. L90: How many stake measurements are excluded?

Response: 3, 3, 6 stakes could not be remeasured in 2011, 2013, 2024, respectively. Of the 196 height records from 49 stakes during the four times, 15 records (7.7 %) were missing. We have quantified the missing stake height records and add information to Sect 2.1.1 (page 4, lines 102-103).

9. Section 2.1.2: Details on the instrumental setup of the AWS are missing, notably how subsurface temperature is measured, whether the height of the instruments above the ground surface is measured, and how this height has evolved over the observation period.

Response: We have provided additional details of the AWS. The modification is as follows (page 4, lines 108-112):

“The AWS measures air temperature and wind speed at heights of 1, 2, 4 m above the snow surface. The 4 m air temperature, relative humidity, and wind speed were used in the sublimation and deposition calculation. The thermistors were initially installed at the depth of 0.1, 1, 3, and 10 m below the surface and the 0.1 m snow temperature was used for subsurface temperature. The snow surface rose by 1.58 m from January 2005 to December 2024.”

10. L105: Add an evaluation of ERA5 against the AWS for the common period, for all variables used in the article.

Response: We have added a comparison between ERA5 and the AWS over the common period using daily mean values. We utilized hourly data from the ERA5 grid point located at 80.5 °S, 77.25 °E. AWS daily means were retained only for days with at least 19 hours of quality controlled observations. We evaluated ERA5 2 m air temperature, skin temperature, surface pressure, and 4 m wind speed. Before comparison, we adjusted the ERA5 10 m wind speed to the AWS height of 4 m using a neutral logarithmic profile with $z_0 = 1.5 \times 10^{-3}$. To minimize the impact of mismatch observation heights, we did not compare the AWS 4 m air temperature. Additionally, ERA5 does not provide a humidity variable directly comparable to the AWS 4 m humidity, and the AWS lacks direct precipitation measurements, these variables were not evaluated.

The results indicate that ERA5 captures the observed variations in air temperature and surface pressure reasonably well. For air temperature, the mean bias (ERA5 – AWS), RMSE, and correlation coefficient are 0.78 °C, 3.57 °C, and 0.97, respectively. Surface pressure exhibits almost identical temporal variations to the observations ($r = 1.00$), with a mean bias and RMSE of 2.11 hPa and 2.23 hPa. Skin temperature and wind speed exhibits larger discrepancies. For skin temperature, the mean bias, RMSE, and correlation coefficient are 2.59 °C, 8.21 °C, and 0.75. These discrepancy may be attributed to the increasing burial depth of the AWS snow temperature sensor. For wind speed, the mean bias, RMSE, and correlation coefficient are 1.17 m s^{-1} , 1.82 m s^{-1} , and 0.59. ERA5 tends to overestimate wind speed at Dome A. We have added this evaluation to Sect. 2.2 (page 4-5, lines 123-127) and Figure S1.

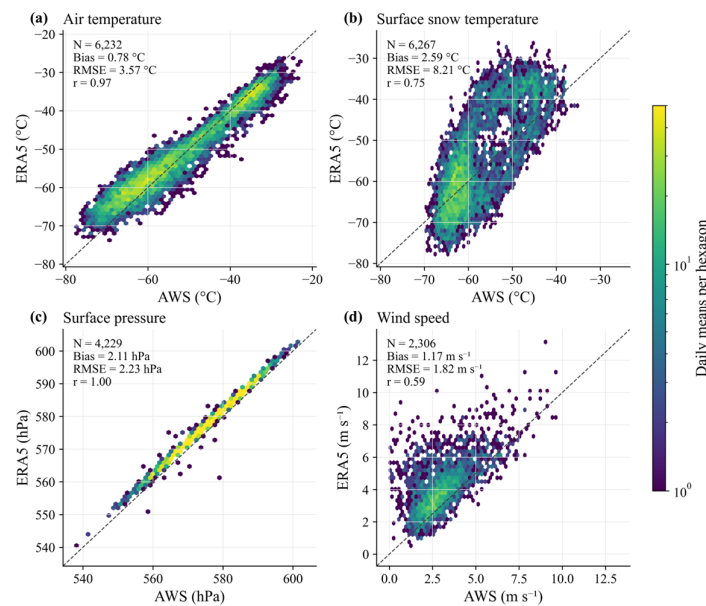


Figure S1. Comparison of ERA5 with Dome A AWS observations using daily mean over their common period during 2005–2024. (a) ERA5 2 m air temperature versus AWS 2 m air temperature. (b) ERA5 skin temperature versus AWS near-surface snow temperature. (c) Surface pressure. (d) Wind speed, before comparison, we adjusted the ERA5 10 m wind speed to the AWS height of 4 m using a neutral logarithmic profile with $z_0 = 1.5 \times 10^{-3}$. N is the number of valid daily means

after quality control. Bias is defined as ERA5 minus AWS. RMSE and r denote the root mean square error and the Pearson correlation coefficient.”

11. Throughout the article, but particularly in Section 2.4.1, units are missing for many variables. For every variable introduced, the corresponding unit should be given, even when it is an SI unit. Example, L133–140: units for H , A , ρ_{sf} , V_{fc} , ρ_i , V_{ice} , B . This is just one example, as units are missing for a large proportion of the variables introduced in the manuscript.

Response: We checked the manuscript and added the corresponding units for the variables. For example, Sect. 2.4.1 has been revised as follows (page 6, lines 158-164):

“In Eq.(1), H is the snow surface height (m), and $dH(t)/dt$ is the rate of snow height change. $A(t)$ is the net surface mass input ($\text{kg m}^{-2}\text{yr}^{-1}$) including the net of snowfall, sublimation and hoar deposition, ρ_{sf} is the density of the surface snow (kg m^{-3}), and $A(t)/\rho_{sf}$ represents the associated surface rise rate. We prescribe ρ_{sf} as the mean snow density measured at 0.2 m depth whose value is approximately 300 kg m^{-3} across the Dome A stake array. $V_{fc}(t)$ denotes the vertical velocity due to firn densification (m yr^{-1}). $A_b(t)$ is the ablation rate ($\text{kg m}^{-2}\text{yr}^{-1}$), and ρ_i is the density of ice (kg m^{-3}), therefore, $A_b(t)/\rho_i$ is the rate of ablation lowering. V_{ice} denotes the vertical velocity of glacier ice at the firn-ice boundary (m yr^{-1}). B is the bedrock elevation (m) and dB/dt is the vertical bedrock motion (isostatic uplift).

12. Equation (4): It seems to me that the t_z inside the integral should be replaced with t .

Response: We replaced t_z inside the integral with t , while retaining as the time required for a snow layer to reach depth z . The modification is as follows (page 7, lines 182):

$$“A_L(z, t) = 1/t_z \int_{t_z=0 \text{ to } t_z} A(t)dt \quad (4)”$$

13. L171: “consistent with the temporal resolution of the ERA5 forcing data” — ERA5 is available at hourly resolution, so I do not understand this justification for working at a monthly time step.

Response: The monthly time step was selected because our simulation focuses on the long-term evolution of firn densification and firn densification responses to change in accumulation and temperature extend from approximately annual to multi-year timescales (Li and Zwally, 2015). We have revised the manuscript in Sect. 2.4.2 (page 8, lines 202-205).

14. Section 2.5: A justification is missing for the choice of bulk transfer coefficients, along with an estimate of how this choice, together with the simplified flux formulation adopted, may affect the estimated condensation and sublimation fluxes.

Response: The coefficient $C_E=0.00129$ under stable conditions and $C_E=0.002$ under unstable conditions were retained because we used the same bulk-aerodynamic

framework by Ding et al. (2016). We recalculated the hoar deposition and sublimation fluxes for 699 days with complete hourly observations using bulk-aerodynamic flux equations with stability corrections based on Monin-Obukhov similarity theory following Ding et al. (2020). The differences reflect the effects of replacing the two transfer coefficients with a turbulent transfer formulation that accounts for atmospheric stability and surface roughness. Stability corrections were applied and the roughness lengths were parameterized following Andreas (1987). A momentum roughness length of $z_0=10^{-4}$ m was used as the reference.

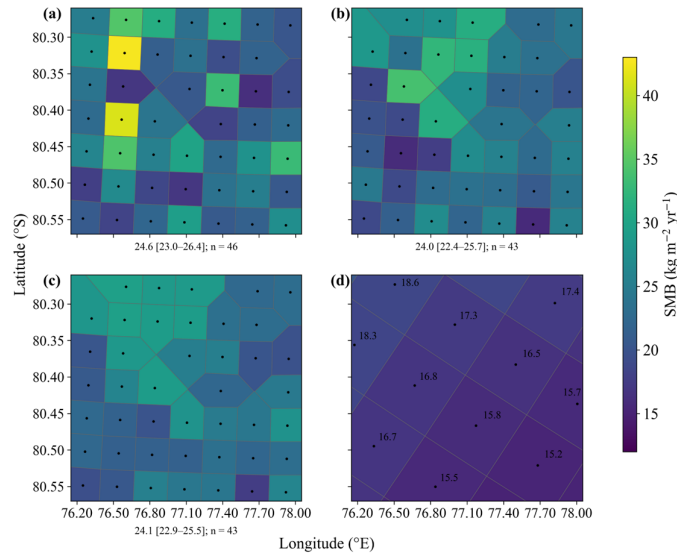
For the moderate stability ($|z/L| \leq 1$), MO theory estimates reduced sublimation by 11.7 % and hoar deposition by 28.8 %. When the comparing was extended to include hours with stronger atmospheric stability, the corresponding reductions increased to 15.6 % and 63.2 %. The greater sensitivity of hoar deposition is likely related to its occurrence mainly under stable atmospheric conditions. We have added the justification to Sect. 2.5 (page 9, lines 235-236) and discussion to Sect. 4.3 (page 19, lines 484-488).

15. L278–279: It is wind divergence over ridges and convergence in valleys that causes erosion on ridges and deposition in valleys.

Response: Thanks for this helpful clarification. Wind divergence and convergence provide a more appropriate description of the mechanism responsible for snow redistribution. We have revised the corresponding sentence accordingly (page 13, lines 349-352).

16. Figure 5: If you wish to keep the divergent blue/red colormap, I would suggest using $24 \text{ kg m}^{-2} \text{ yr}^{-1}$ (your mean SMB estimate) as the central value of the colorbar, and stating this in the figure caption, as divergent colormaps require a meaningful central value. Alternatively, if you would prefer not to center the colorbar on $24 \text{ kg m}^{-2} \text{ yr}^{-1}$, I would recommend using a continuous (non-divergent) colormap for SMB, such as 'viridis' or 'YlGnBu' in Python, for example.

Response: We have updated the diverging colorbar in Figure 5 to viridis. The modification is as follows (page 15, lines 354):



17. L301–302: I think that using daily values instead of hourly values may introduce substantial biases in the flux estimates. The error resulting from this assumption should be estimated using the days for which hourly data are available.

Response: We conducted a sensitivity analyze using 699 days with complete hourly observations of all variables required for the bulk-aerodynamic calculation. LE was calculated using hourly wind speed and the daily-mean wind speed. We have added this sensitivity analyze to Sect. 4.3 and Fig. S4. The modification is as follows:

(1) Sect. 4.3 (page 19, lines 480-484):

“A sensitivity analyze was using 699 days with complete hourly observations of all variables required for the bulk-aerodynamic calculation (Fig. S4). LE was calculated using either the hourly wind speed or the daily-mean wind speed. The two estimates agreed closely ($R^2 = 0.995$), and the daily mean wind approach produced a mean bias of -0.022 W m^{-2} . Sublimation was underestimate by 4.7 %, whereas deposition was overestimated by 2.3 %. The distribution of daily difference was near zero, with a small negative skew and several larger negative differences.”

(1) Figure S4:

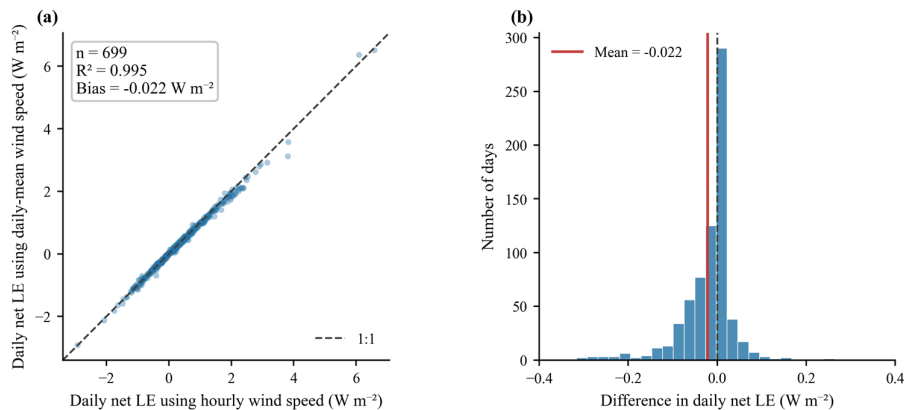


Figure S4. Sensitivity of daily net LE to use of daily mean wind speed with complete hourly wind speed. (a) Comparison of daily net LE use daily mean wind speed and hourly wind speed. The dashed line denotes the 1:1 relationship. (b) Distribution of the daily differences (daily mean wind estimate minus hourly wind estimate). The red line marks the mean bias, and the dashed line marks zero.”

18. Section 3.5: An evaluation of the RACMO sublimation flux should be added to complete the study.

Response: We have added an evaluation of the RACMO sublimation flux. We used both the RACMO total sublimation, which includes sublimation of suspended snow in the atmosphere caused by blowing snow, and the latent heat flux, which provides a more direct comparison with the AWS surface vapor exchange. We define sublimation as positive and deposition as negative.

The comparison shows a substantial difference between the AWS estimate and RACMO. The AWS estimates show pronounced sublimation between November and January, while the RACMO consistently negative across the entire climatological mean annual cycle. Base on the 237 valid overlapping months, the comparison between AWS and RACMO derived from latent heat flux gives $r=-0.27$, an RMSE of $0.508 \text{ mm w.e. month}^{-1}$ and a mean bias (RACMO -AWS) of $-0.282 \text{ mm w.e. month}^{-1}$. The RACMO sublimation shows a very similar seasonal pattern to the latent heat flux estimate with no pronounced summer sublimation maximum. This evaluation has added to Sect. 3.5 (page 17, lines 405-410) and Figure C1 (page 23, lines 547-554). The modification is as follows:

“Appendix C1

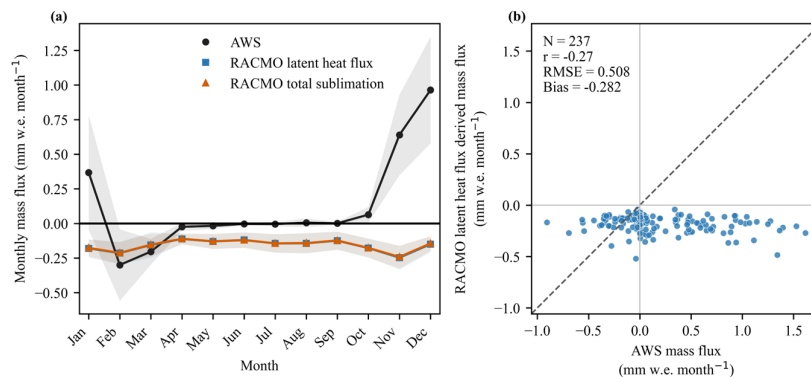


Figure C1. Evaluation of RACMO2.4p1 monthly sublimation and hoar deposition against the AWS estimates at Dome A. (a) Monthly climatological means of the sublimation and hoar deposition mass fluxes from AWS, RACMO surface mass flux derived from the latent heat flux, and the RACMO total sublimation component. The data represent 237 common valid months from February 2005 to December 2024. Shading indicates ± 1 interannual standard deviation. (b) Comparison of the AWS estimates against the RACMO mass flux derived from latent heat flux. Positive values denote sublimation, and negative values denote deposition. The nearest RACMO grid point, located 2.8 km from the AWS, is used.

19. L321: I find "critical" too strong a term; I suggest replacing it with the actual value

(~9%).

Response: We have replaced this qualitative description with the quantified result derived in this study. The modification is as follows (page 18, lines 426-428):

“While firn compaction is often negligible in high accumulation regions over short observation periods, our results show that accounting for firn densification increases the estimated SMB at Dome A by approximately 8.8 % over 2008–2024.”

References:

Andreas, E. L.: A theory for the scalar roughness and the scalar transfer coefficients over snow and sea ice, *Boundary-Layer Meteorol*, 38, 159–184, <https://doi.org/10.1007/BF00121562>, 1987.

Ding, M., Yang, D., Van den Broeke, M. R., Allison, I., Xiao, C., Qin, D., and Huai, B.: The surface energy balance at Panda 1 Station, Princess Elizabeth Land: A typical katabatic wind region in East Antarctica, *Journal of Geophysical Research: Atmospheres*, 125, e2019JD030378, <https://doi.org/10.1029/2019JD030378>, 2020.

Howat, I. M.: Temporal variability in snow accumulation and density at Summit Camp, Greenland Ice Sheet, *Journal of Glaciology*, 68, 1076–1084, <https://doi.org/10.1017/jog.2022.21>, 2022.

Li, J. and Zwally, H. J.: Response times of ice-sheet surface heights to changes in the rate of Antarctic firn compaction caused by accumulation and temperature variations, *Journal of Glaciology*, 61, 1037–1047, <https://doi.org/10.3189/2015JoG14J182>, 2015.