Snow accumulation rates at Concordia Station, Antarctica, observed by stake farms

Stefanini et al., 2025

Editor: Lei Geng

The Antarctic surface mass balance is a key factor and an important source of uncertainty in understanding the current total Antarctic mass balance and its contribution to global sea level rise, and thus deserves to be studied fully. However, Antarctic SMB measurements remain challenging due to its isolated location and harsh environment, which is even more evident in the Antarctic interior, although some continuous measurements have been maintained at South Pole, Vostok, and Dome F, etc. This study utilized stake farms installed around Concordia Station by Italy and France, combined with reanalysis and regional climate models to assess the SMB in the vicinity of Dome C, providing important information about the interior Antarctic SMB. Overall, this study is well done, but there are still some places that need to be enhanced to make the study completer and more meaningful. Therefore, I would recommend the authors to make a major revision of the manuscript before it can be published.

Thanks to devote time to the review of our manuscript and for the helpful suggestions.

Specific comments:

1. L27-28: In the Abstract, the authors should specifically point out what kind of effects of buildings on SMB, e.g. whether it increases or decreases the snow accumulation rate? Do the buildings primarily influence the snow blowing or snow falling process? If possible, explain in detail the dynamical mechanisms by which buildings located upwind may have an impact on snowfall.

This part has been added to the abstract, after line 27: "In the hyper-arid environment of Dome C, snow accumulation is largely governed by post-depositional processes such as wind redistribution and clear-sky precipitation. Elevated buildings alter the wind field, enhancing erosion beneath them and forming snowdrifts leeward and laterally, which may explain accumulation differences between the ITA and FRA stake fields."

2. Introduction: The authors have described the significance and some advances on Antarctic SMB measurements, to which I suggest some additions. On the one hand, please add more articles on the factors and mechanisms affecting snow accumulation variations in Antarctic interior, which can include the Dome C, South Pole, Vostok, Dome A and Dome F. On the other hand, there are a number of findings based on deep ice cores and stake farms available at these stations (e.g., Fujita et al., 2011; Lazzara et al., 2012), suggesting that the authors include them in the introduction. Moreover, I recommended the authors to cite two papers (Wang et al., 2021; 2023), they integrated the Antarctic SMB observations and Automatic Weather Stations, which can provide more details for the Introduction and make it completer. In the quality-controlled SMB dataset, in addition to stakes and stake farms, SMB measurements based on other means, such as snow pits, ice cores, ultrasonic sounders, and ground-penetrating radar were collected. They also introduce some AWS instrument installation, sensor and data quality control standards, which includes the Dome C and may be useful for introducing AWS accuracy in this study. A few are listed here, and I suggest that authors actively search for more literature and summarize them.

Fujita, S., Holmlund, P., Andersson, I., et al. (2011). Spatial and temporal variability of snow accumulation rate on the East Antarctic ice divide between Dome Fuji and EPICA DML, The Cryosphere, 5, 1057–1081, https://doi.org/10.5194/tc-5-1057-2011.

Lazzara, M. A., Keller, L. M., Markle, T., & Gallagher, J. (2012). Fifty-year Amundsen–Scott South Pole station surface climatology. Atmospheric Research, 118, 240-259.

Wang, Y., Ding, M., Reijmer, C. H., et al. (2021). The AntSMB dataset: a comprehensive compilation of surface mass balance field observations over the Antarctic Ice Sheet, Earth Syst. Sci. Data, 13, 3057–3074, https://doi.org/10.5194/essd-13-3057-2021.

Wang, Y., Zhang, X., Ning, W., et al. (2023). The AntAWS dataset: a compilation of Antarctic automatic weather station observations, Earth Syst. Sci. Data, 15, 411–429, https://doi.org/10.5194/essd-15-411-2023.

This part has been added to the Introduction section, after line 43:

"A large fraction (two thirds) of the annual accumulation at Dome C comes from clear-sky precipitation, such as diamond dust and vapor condensation, rather than conventional snowfall events (Stenni et al., 2016). While snowfall and diamond dust provide the baseline input, post-depositional processes exert the greatest influence on spatial and temporal variability. Inland accumulation is primarily driven by fluctuations in snowfall, which dominate interannual variability in SMB (Noël et al., 2023). However, the apparent uniformity of precipitation over tens to hundreds of kilometres is disrupted by wind and surface processes, which modulate local accumulation through redistribution across microtopographic features (Fujita et al., 2011). Wind is consistently identified as the dominant control across the East Antarctic Plateau. Processes such as drifting snow, erosion, and redistribution create highly variable features including sastrugi, dunes, and megadunes, which contribute to substantial local heterogeneity (Frezzotti et al., 2005; Eisen et al., 2008). Sublimation—both surface and wind-driven—further reduces accumulation, and in particularly dry areas like Dome C, Dome Fuji, and Vostok, it may cancel out a significant fraction of snowfall (Eisen et al., 2008). Over the central plateau, katabatic winds actively shape the surface, driving strong spatial variability even where precipitation is minimal (Lazzara et al., 2012). At the South Pole, for instance, annual accumulation decreased significantly from 1983 to 2010, largely attributed to changes in wind and sublimation patterns rather than reductions in snowfall (Lazzara et al., 2012). Topographic effects are also critical: Dome sites generally exhibit lower spatial variability (3–9%) compared to regions with complex surface morphology, where variability may exceed 40% (Eisen et al., 2008). Small-scale features such as sastrugi, wind crusts, and megadunes introduce accumulation noise two to four times the mean, occasionally resulting in multi-year ablation (Frezzotti et al., 2005). On larger spatial scales, Dome Fuji records demonstrate how accumulation differences are strongly correlated with position relative to ice divides and prevailing wind directions, and are further modulated by elevation and distance from moisture sources (Oyabu et al., 2023). Overall, spatial variability at kilometre scales is an order of magnitude greater than temporal variability at decadal to secular scales (Frezzotti et al., 2005). This highlights why dome sites such as Dome C are often favoured for paleoclimate reconstructions: their relatively stable conditions reduce the noise introduced by local post-depositional processes, even though wind redistribution and sublimation remain significant factors (Frezzotti et al., 2005)."

Furthermore, when discussing the AWSs, this part has been added at line 60:

"Besides, stations are unevenly distributed: clustered near coastal regions, with only a few inland installed on the East Antarctic Plateau, including Dome C, Dome F, Vostok, and other interior sites (Wang et al., 2023). AWSs, by capturing long-term records of key drivers—such as wind, humidity, and temperature—enhance our understanding of how atmospheric processes impact SMB in remote high-plateau regions. Long-term SMB observations are rare but invaluable. Some AWSs are equipped with ultrasonic sensors to measure snow surface height changes by detecting the vertical distance to the surface, but the uncertainty of the measurements is not sufficient to properly examine the small snow accumulation events that usually occur in the interior of the East Antarctic Plateau (Wang et al., 2021). The AntSMB dataset comprises observations from 675 sites across Antarctica, including daily, annual, and multi-year records derived from ice cores, snow pits, stake farms, ultrasonic sounders, and ground-penetrating radar. The dataset reveals large spatial heterogeneity in accumulation driven by local processes like wind redistribution, slope effects, and surface roughness, which are pronounced across interior plateau sites. By integrating multiple measurement types (e.g. stakes, cores, radar), the dataset allows quantification of the relative impact of precipitation supply, erosion/deposition, and surface sublimation, clarifying which processes dominate at interior sites (Eisen et al. 2008; Wang et al., 2021). The combined analysis of GPR profiles, firn cores, and stake measurements indicates that Dome C exhibits remarkable spatial homogeneity at the regional scale, with only minor local variations in snow accumulation primarily driven by surface microtopography and prevailing wind patterns (Urbini et al., 2008). Temporal variability in accumulation rates appears limited over decadal to centennial scales, as confirmed by firn-core records, although interannual fluctuations linked to episodic wind-driven redistribution are evident. The consistency between point-scale observations and GPR-derived stratigraphy supports the reliability of radar methods for spatial interpolation in this area. Overall, the low flow velocity, minimal surface undulation, and stable accumulation regime reaffirm Dome C as an optimal site for deep ice core drilling and long-term paleoclimate reconstructions (Urbini et al., 2008)."

3. Data and methods: 2.2 Reanalysis and regional climate models: Please detail how SMB or snow accumulation rates from reanalysis (or regional climate models) are calculated. Is it precipitation minus evaporation? I see a similar description in the Results, but they should have been made clear in the second section.

The sentence "SMB has been calculated as the sum of the snowfall and snow deposition minus snow sublimation" has been added at the end of Section 2.2.

4. I would strongly encourage the authors to go into more detail about the sites and sensors, their measurement metrics and possible errors in section 2.4. Perhaps a table could be created.

The following text and table have been added to the text, after line 173:

"Hourly wind speed and direction are derived from the observations of the Italian AWS Concordia (75.105°S 123.309°E, 3230 m, approximately 850 m far from the Station), managed by the Italian Antarctic Meteo-Climatological Observatory of the PNRA, which are available for the 2005-2023 period; a Vaisala Milos 520 model station is installed 3 m above the ground and equipped with both heated and unheated aerovane, and an ultrasonic wind sensor WS425 (https://www.climantartide.it/strumenti/aws/Concordia/index.php?lang=en). Details on sensors and technical data are reported in Table 1. Wind speed and direction are provided hourly, with a resolution of 1 knot and 10 degrees respectively. Wind speed is then reported in m/s. Other AWSs are present in the Dome C area, but this is the only one with heated sensors, not affected by frost.

	Vaisala WAA151 [1]	**WAV151 [1]**	**WS425 [2]**	
	wind speed	**wind direction**	**wind speed**	**wind direction**
Sensor/transducer type	Cup anemometer/opto-chopper	Optical code disc	Ultrasonic wind sensor	
Observation range	0.4–75 m/s	0–360° (at wind speed 0.4–75 m/s)	0 – 65 m/s	0–360°
Starting threshold	< 0.5 m/s	< 0.4 m/s	virtually zero	virtually zero
Resolution	0.1 m/s	±2.8°	0.1 m/s	1°
Accuracy	max ±0.5 m/s (within 0.4–60 m/s)	Better than ±3°	±0.135 m/s	±2.0°

[1] https://docs.vaisala.com/v/u/B210382EN-J/en-US

[2] WS425 Users Guide M210361EN-E

Table 1. Description of the wind sensors of the Concordia AWS used in this study."

Moreover, this part has been added in Section 2.1, after line 106, to describe the man-made structures present in the area:

"The facility consists of a winter station made up of two interconnected cylinders linked to the power plant, and a summer camp (which also serves as an emergency camp during winter). Each cylinder of the winter station has a diameter of 18.5 m and a height of 11 m (2955 m^3), and is divided into three floors, providing a total of 250 m^2 of usable surface. The total height above the ice exceeds 14 m, since each structure rests on six large adjustable iron supports designed to compensate for variations in ice thickness (https://www.pnra.aq/it/stazione-concordia). The main structures and facilities are shown in Figure 1. ATMOS and PHYSICS are shelters located near the Italian stake farms composed of 8 and 4 coupled containers, respectively (https://www.pnra.aq/it/laboratori-e-facilities-concordia, an aerial view of the facility is shown in Figure S1). Besides, every year several tons of snow are cleared from the buildings and other structures, including the towers and the summer camp, and transported north using a Pisten Bully.

Finally, Figure 1 has been modified accordingly and Figure S1 now shows a photograph of Concordia Station.

5. Results: I would suggest that the authors place sections 4.1 and 4.2 in the Results rather than in the Discussion. In terms of content, they are more of a description of the Results.

Sections 4.1 and 4.2 have been moved to the Results part, now they are Section 3.3 and 3.4, respectively.

6. L222: This algorithm may artificially create some differences between reanalyzes, regional climate models and stake farms. Considering the temporal and spatial continuity of the simulation results, it is recommended that the authors divide the accumulation period based on measurements (possibly based on French stake farms). Although not all the datasets are available with daily resolution, the authors should have added at least some results from products capable of providing daily resolution data as a validation, such as ERA5 and MERRA-2.

The comparison between the temporal evolution of accumulation derived from our algorithm with results from products that provide daily resolution data, specifically ERA5 and MERRA-2, has already been performed. The yearly comparisons were performed to assess the consistency of our results and are presented in the Supplementary Material (Table S1). We considered the timing of accumulation periods based on available measurements, i.e., those from the French stake farms, to the extent allowed by the data coverage.

7. L370-376: I don't think the description here is adequate, please explain in conjunction with simulations or other studies how buildings have affected the snow accumulation rate, especially when the atmospheric aquifer is not primarily concentrated in the lower atmosphere. Also, is the main effect of buildings reducing or increasing snowfall, or changing the wind scouring of deposited snow? This is similar to the 1st comment. --L378: ablation-->wind ablation.

This explanation has been added to the text:

"Model tests using real snow particles in cold-climate wind tunnels demonstrate that airflow accelerates beneath buildings elevated above the snow surface, which causes increased surface stress and erosion directly beneath the structure. Snow eroded upwind is deposited downwind of the building, forming concentrated drifts in the wake region. This redistribution results in reduced accumulation immediately near the building and increased snow loads farther leeward (Mitsuhashi et al., 1983; Kwok et al., 1992; Delpech et al., 1998; Yamagishi et al., 2012), with the building elevation, shape, and roof inclination also playing a role (Yamagishi et al., 2012). However, further leeward, a slight scouring zone emerges with less accumulation with respect to the adjacent zones (Moore et al., 1994, Thiis, 2003; Nara et al., 2025), where the ITA stake farm is located. Beyond the turbulent wake, wind resumes its ambient plateau flow regime. Besides, under this hyper-arid conditions, post-depositional processes like wind drift, sublimation, and hoar frost formation often dominate over the initial snowfall in determining the final surface accumulation (Frezzotti et al., 2005). Additionally, a large fraction of the annual accumulation (two thirds) comes from clear-sky precipitation, such as diamond dust and vapor condensation, rather than conventional snowfall events (Stenni et al., 2016).

Furthermore, enhanced snow accumulation zones develop on both side of the buildings, extending also leeward at a great distance from them, more than 10 times the height of the structures, forming a horseshoe shape (Thiis, 2003; Nara et al., 2025). This effect could explain the higher accumulation in the ITA field with respect to the FRA one when snowfall and wind from the north occur: FRA is probably well beyond the turbulent wake leeward the buildings, but ITA is likely affected by increased accumulation due to lateral snowdrifts."

8. L381-383: “Besides, black carbon produced by the Station can also affect the albedo causing differences in surface temperature, sublimation, and surface hoar frost formation, impacting the final snow accumulation”. It's an interesting thing, so is it possible to provide more descriptions about how to influence them (Just cite more papers to explain it). In particular, I would like to know what is the source of these black carbon? Also, if they have a large effect on the surface temperature, sublimation, and surface hoar frost formation, even the surface mass balance, does this mean that expedition activities will obviously affect the ice, and what should be done to minimize this effect?

The snowpack’s energy budget and photochemistry are strongly influenced by how solar radiation penetrates the snow. Light decreases exponentially with depth, governed by the asymptotic flux extinction coefficient, which —like albedo— depends on snow grain shape and size (Bohren and Barkstrom, 1974). Even trace amounts of impurities can markedly reduce light penetration (Warren et al., 2006). Since the establishment of Concordia Station in 2003, elevated black carbon (BC) levels have been detected in the surrounding snowpack, over three times higher than pre-2003 values (Warren et al., 2006). This contamination reduces light penetration, resulting in a shallower e-folding depth compared with pristine snow (Warren et al., 2006; France et al., 2011; Libois et al., 2013). The station has adopted measures to reduce black carbon, and while its impact is not currently being evaluated, it is certainly not negligible.

Helmig et al. (2020) reported that, despite sampling snow pits in the clean-air sector ~1 km southwest of the Station, exhaust plumes from camp activities —mainly power generation— reached the site on ~50 occasions during their 1.2-year study. They observed sharp spikes in NO_x concentrations, up to 1,000 times ambient background. However, they did not measure BC deposition, nor did they assess snow albedo, grain size, or surface temperature. Their focus remained on photochemical tracers (NO_x, O_3) and snow chemistry, rather than radiative or thermodynamic effects.

By contrast, studies near coastal Antarctic Peninsula stations with greater human activity, including popular tourist landing sites, show that BC deposition can reduce albedo, accelerate melting, and contribute to surface warming (Δalbedo ≈ 0.001–0.004; local forcing ~0.25–1 W/m²) (Cordero et al., 2022). Yet, Concordia Station lies on the high Antarctic Plateau, far more remote, where BC emissions and deposition are orders of magnitude lower than at coastal facilities. To date, no evidence clearly demonstrates that BC from Concordia Station significantly affects local albedo, snow grain size, or surface temperature.

In conclusion, while NO_x and O_3 impacts from station activities are documented, direct evidence linking Concordia’s BC emissions to snow radiative properties remains absent. Potential impacts can be inferred from other Antarctic studies, but such extrapolations remain hypothetical and beyond the aim of this analysis. These concepts, summarized, have been added to the manuscript.

9. Discussion: I don't think the sections 4.3 and 4.4 are well delineated. A more sensible approach would be to first describe the effects of wind on snow accumulation rates, and then discuss their interaction with station buildings in more detail in the second section.

Sections 4.3 and 4.4 have been swapped as suggested.

10. Current analyses of the effect of wind on snow accumulation rates have focused on resolving the differences between the two stake farms, and whether it is possible to provide more information on whether wind direction, wind speed, or other surface processes influence the overall accumulation rate results than spatial variability.

Morphology certainly affects observations, and its effects should emerge if the disturbance were regular. However, no statistically significant difference was found between the two axes of the stake cross, either in terms of mean values or variability. Moreover, a preliminary analysis of surface elevation fluctuations from the REMA dataset suggests the presence of 200–400 m wide undulations, which appear to have remained stationary over the past 15 years.

11. The authors discussed the effects of a number of localized factors on Dome C snow accumulation rates, and as the authors cited a few studies, these have actually been mentioned before. Therefore, to add an innovative point, I suggest that the authors add some results to discuss the factors controlling the variability or interannual fluctuations in snow accumulation rates (since the authors claim that there is not a significant trend), and that studies could be carried out in terms of factors such as local

temperatures and clear-sky precipitation, then to discuss the impacts of large-scale forcing such as SAM and ENSO on the snow accumulation rate.

We appreciate the reviewer's suggestion regarding the potential influence of large-scale climate modes such as SAM and ENSO on snow accumulation variability at Dome C. However, this analysis goes beyond the scope of the present work, which focuses primarily on local-scale factors influencing recent accumulation patterns. Additionally, the length of the available time series is not sufficient to robustly investigate potential links with the periodicities associated with SAM and ENSO. We agree that this is an interesting direction for future research.

12. Figure 12: Explain any reference for the selection of the threshold.

The method for selecting the threshold has been added to the caption.

13. L439-L441: Such events have been widely watched and studied, and I encourage authors to analyze the accumulation values during several extreme events and judge their contribution to the annual accumulation values, based on observational data available at monthly resolution.

We thank the reviewer for this constructive suggestion. We agree that investigating the contribution of extreme events to annual accumulation would be valuable. However, such an analysis requires a longer and more complete record of high-resolution observational data, which is currently not available with sufficient temporal coverage for Dome C. As our study is based on a relatively short time series, it does not allow for a robust assessment of the frequency or impact of such events on interannual variability. Nonetheless, we acknowledge the importance of this aspect and will mention it as a promising avenue for future research.

14. A small question: the anomalies calculated in this manuscript are relative anomalies (%), could absolute anomalies (cm or mm) be provided for comparison? These can be placed in the supplementary file.

The Figure S2b has been added to the Supplementary material, showing the yearly SMB anomaly with respect to the 2004-2023 climatology, in mm of water equivalent.

15. Improvement of the figure: Figure 1: This figure could be improved. First, the font of a), b) and c) is too big compared to the rest of the information on this figure and I would suggest that the authors adjust the font size. Also, it is recommended that the three subfigures be placed on one page after stitching them together instead of splitting them on two pages.

--Figure 1 and Figure 2: I suggest that the author remove the white area from the figure that doesn't present any information.

--Figures 4 and 5 can be stitched together as sub-figures, which can be easily compared by readers.

Font of Figure 1 has been modified, and the images have been merged in a single figure. Moreover, more information has been added to Figure 1, and white space has been removed from Figures 1 and 2. Figures 4 and 5 have been stitched together.