Response to Review of Climate Controls on Snowfall at Coastal West Antarctic Ice Rises - Potential Ice Core Sites

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We thank Referee 2 for their careful and constructive comments on our manuscript. Their feedback has meaningfully strengthened the work. Below, we respond to each comment in turn. Reviewer comments are shown in italics, and our responses follow in regular text. Where applicable, we note revisions made to the manuscript.

Reviewer Comment #2:

Overview Comments:

This article presents the relationship between precipitation at Antarctic ice rises and several key atmospheric circulation or oceanic indicators (Southern Annular Mode, Amundsen Sea Low, and El Nino-Southern Oscillation). Section 1 summarizes previous Antarctic ice core sites, and presents the potential importance of future ice core drilling at Antarctic ice rises. Section 2 examines the reanalysis data and conclude to use ERA-5 in further analysis. Section 3 is the main results of the article, presenting the correlation between precipitation at 13 potential ice core sites from WAIS and atmospheric circulation indices. The analysis led to two main conclusions for the proposed ice core sites: [1] the West Sector of the WAIS coast, where precipitation is strongly influenced by Southern Hemisphere westerly winds; and [2] the East Sector, where precipitation is strongly influenced by synoptic-scale pressure systems along the Bellingshausen Sea.

I believe the methods used have not been sufficiently considered for the research purpose of assessing future ice core sites for climate reconstruction. The most critical point is that ice cores do not necessarily record precipitation; they record surface mass balance.
Surface mass balance is determined by several processes, including precipitation, refreezing of water, surface melting, sublimation of ice, and blowing snow erosion (e.g. Equation 2 of van Dalum et al., (2025)). At high annual-mean temperatures like those in Table 1, significant melting can occur during austral summer, which makes it very hard to reconstruct past precipitation. To address this issue, a global reanalysis like ERA-5 and MERRA-2 has very limited ability to address surface mass balance. Instead, I recommend that authors analyse regional climate model simulations. Recently, several regional climate simulations have been published (van Delum et al., 2025; Agosta et al., 2019). As these regional climate models have been evaluated by number of observed surface mass balance observations, These datasets have a certain degree of credibility. In fact, the Antarctic regional climate model, RACMO, has been used to examine ice-core data (Thomas et al., 2017). As those regional climate simulations were

forced by reanalysis including ERA-5, I think the analysis in the current preprint can be utilized in the same manner.

We thank Reviewer #2 for engaging seriously with the methodological foundations of the study. We believe the concern, while worth addressing directly, does not undermine the core analysis, for the reasons we explain in detail below. The key point is that our study is focused on interannual variability between atmospheric circulation modes and local precipitation, a relationship that is robust in ERA5 and directly relevant to ice core site selection. The distinction between precipitation and SMB matters most for absolute magnitudes and long-term trends; it has a much smaller effect on the year-to-year correlation structure that we base our conclusions on, especially in coastal Antarctica where snowfall is highest anywhere on the continent. Additionally, Antarctic surface snow melt is limited particularly along the coast of West Antarctica and becomes even more so at locations elevated above low-lying ice shelves, such as the ice rises that are the subject here, all of which are elevated several hundred meters above sea level (see Table 1).

Major Comments

1. *Section 2 presents the correlation between ERA-5 and MERRA-2, but this analysis does not guarantee that these models have sufficient ability in simulating precipitation. I recommend using the surface mass balance from the Antarctic regional model(s), as these models have been evaluated by observations. The same applies for surface air temperature.*

We appreciate the depth of this comment and address the following three points: the precipitation–SMB relationship at these specific sites, the independence (or lack thereof) of regional climate models (RCMs), and the melting concern.

1. Precipitation as a proxy for SMB at high-accumulation coastal ice rises. The reviewer correctly notes that ice cores record SMB rather than precipitation directly, and that SMB is determined by multiple processes including precipitation, refreezing, surface melting, sublimation, and blowing snow erosion and redeposition (Lenaerts et al., 2019, doi: 10.1029/2018RG000622). We agree this distinction is important and have added clarifying text to Section 2.1 and the Discussion to address it explicitly.

At the high-accumulation coastal ice rises studied here (mean annual accumulation 0.58–1.06 m w.e. yr^{-1}, Table 1), precipitation is the dominant SMB term and non-precipitation losses are small in relative terms. Surface sublimation depends on the surface-to-air humidity gradient and wind speed and is suppressed when near-surface air moisture is high (Lenaerts et al., 2019); frequent precipitation and proximity to the Southern Ocean maintain persistently moist near-surface conditions at our sites. Drifting snow sublimation, the largest ablation term continent-wide, removes approximately 6% of annually precipitated snow when integrated across the ice sheet (Lenaerts & van den Broeke, 2012, doi: 10.1029/2010JD015419), and this fraction is further reduced in high-accumulation coastal regions where near-surface air is frequently near saturation and summer melt consolidates the snow surface, limiting the potential for snowdrift (Lenaerts et al., 2012a, doi: 10.1029/2011JD016145). Runoff is negligible at these sites because nearly all meltwater refreezes (Lenaerts and van den Broeke, 2012). As a consequence, interannual SMB variability largely follows the interannual variation in snowfall (Lenaerts et al., 2012b, doi: 10.1029/2011GL050713).

Furthermore, Lenaerts et al. (2019) explicitly identify the Amundsen-Bellingshausen region as exhibiting the largest intra-annual and interannual SMB variability on the Antarctic continent, driven primarily by southward moisture transport, the same atmospheric circulation signal captured by our ERA5 precipitation correlations. This supports our contention that ERA5 precipitation captures the dominant driver of interannual SMB variability at these specific sites.

This equivalence is well established in the literature: Medley and Thomas (2019) use reanalysis P−E as a proxy for snow accumulation across the grounded Antarctic Ice Sheet, restricting this framework to regions of positive SMB, the same regime characterizing our sites. In the revised manuscript, we compute ERA5 P-E at each site and confirm that the correlation structure with climate indices is not meaningfully affected by the inclusion of the evaporation term, providing further support that precipitation captures the dominant interannual SMB signal at these locations.

2. ERA5 is appropriate for assessing interannual variability, and RCMs are not independent. We agree that RACMO (van Dalum et al., 2025) and MAR (Agosta et al., 2019) are valuable datasets and have been evaluated against observed SMB and used in ice core studies (Thomas et al., 2017). Therefore, we have added citations to both in the revised manuscript. That said, we want to flag two points to discuss whether switching to RCM-derived SMB would actually change our conclusions.

First, as the reviewer notes, these regional climate simulations are themselves forced by ERA5 lateral boundary conditions. This suggests that their large-scale circulation patterns, and therefore their interannual precipitation variability, are not independent of ERA5. The added value of RACMO and MAR is primarily in representing local surface energy balance, orographic precipitation, and blowing snow at fine scales, not in providing an independent check on the large-scale forcing we explore here.

Second, our central question is which climate modes (SAM, ENSO, ASL, regional winds) drive year-to-year variability in accumulation at these sites, not the absolute magnitude of SMB. For that purpose, ERA5 precipitation is appropriate: Medley and Thomas (2019) show that reanalysis products capture a significant fraction of interannual accumulation variability across Antarctica even where absolute magnitudes are biased and explicitly favor reanalyses over regional climate models for this purpose. We have added RCM comparison as a recommended next step for evaluating absolute SMB values and site-specific surface processes, rather than treating it as a prerequisite for the correlation analysis presented here.

3. Surface melt at these sites is limited. We take the melt concern seriously but note that the evidence consistently points to it being negligible at the specific sites studied here. A high-resolution (5.5 km) RACMO2 simulation of coastal West Antarctica, the very RCM the reviewer recommends, finds that surface melt does not frequently occur over most of the grounded ice sheet and is confined to ice shelves (Lenaerts et al., 2018, doi: 10.1017/aog.2017.42). Where melt does occur on ice shelves, it is concentrated in a narrow band near grounding zone margins where warm microclimates develop due to katabatic wind compression (Lenaerts et al., 2018). The elevated summits of the ice rises studied here (397–659 m a.s.l.) are well above these low-lying melt zones.

This is further supported by satellite-based melt flux estimates showing that the Amundsen Sea and Marie Byrd Land coast experiences some of the lowest surface melt rates on the Antarctic continent, consistently near or below several tens of mm w.e. yr^{-1} throughout the 1999–2009 record (Trusel et al., 2013, doi: 10.1002/2013GL058138). The continent-wide survey of Kingslake et al. (2017, doi: 10.1038/nature22049) similarly documents widespread surface meltwater drainage as an ice-shelf phenomenon, occurring on floating ice at or near sea level; none of the 696 drainage systems identified originate on elevated grounded ice features of the type studied here. The mean annual temperatures at our sites (−8.3°C to approximately −14°C in ERA5, Table 1) provide an additional thermodynamic constraint: even under anomalously warm summer conditions, the surface energy available for sustained melt at these elevations is minimal. Additionally, we have direct field experience at Canisteo Peninsula (RAICA project, January 2024, unpublished) and observed no evidence of significant melt in the recovered core stratigraphy, only periodic melt or sun crust layers no thicker than 1–2 millimeters.

On the question of whether RCM melt parameterizations offer a more reliable picture: the Lenaerts et al. (2017) RACMO2 simulation already demonstrates that melt is negligible at grounded, elevated coastal sites in this region. More broadly, melt schemes in existing Antarctic regional models remain poorly constrained in coastal West Antarctica precisely because of the absence of in situ observations, the same gap this manuscript and the RAICA ice core initiative are designed to fill (Lenaerts et al., 2018; Neff, 2020). We have added a paragraph to the Discussion addressing melt, noting the modeled temperature ranges at each site and the Trusel et al. (2013) satellite evidence, while acknowledging that melt will need proper evaluation once cores are recovered.

2. *Table 1: The method used to calculate climate information for each ice rise point is not explained. Is the elevation the elevation of the observed terrain, or the elevation from the*

ERA-5 reanalysis? Also, the temperature and precipitation should have been calculated from ERA-5, but how were they calculated? Are they calculated by bilinear interpolation based on the latitude and longitude? Also, are these annual average temperatures and precipitation values calculated at a single point in the table, or are they averaged over the ice rise? Please clarify.

Thank you, we agree that the table was insufficiently described. We have added the following clarification to Section 2.1 and the Table 1 caption: Maximum elevation values are from MEaSUREs BedMachine Version 3 at 500 m resolution (Morlighem, 2022), representing observed ice surface topography, not ERA5 model orography (which at ~35 km resolution substantially underestimates the height of individual ice rises). Annual temperature and precipitation time series are extracted from ERA5 at the single nearest grid cell (~0.25°) to each ice rise summit coordinate, without bilinear interpolation or spatial averaging over the ice rise. This point-extraction approach is appropriate because ERA5's resolution already represents a spatial average that encompasses the full extent of these relatively small features. Temperature values are ERA5 2-meter air temperature annual means (1979–2022). We have also added °C to the temperature column header and specified precipitation units as m w.e. yr^{-1} (meters water equivalent per year).

Specific comments:

1. *L34: I think Barr & Lovell (2014) does not fit here because the study is Antarctic Morraines.*
    a. Thank you, we agree. We have removed Barr & Lovell (2014), which examines topographic controls on moraine distribution and is not relevant to the WAIS ice dynamics context of Line 34. We have replaced it with Shepherd et al. (2018, doi: 10.1038/s41586-018-0171-6), which is a comprehensive review of satellite-era trends across the Antarctic cryosphere and includes grounded ice mass loss, ice shelf thinning, and ocean-atmosphere forcing in the Amundsen Sea sector, which directly supports the statement at this line.
2. *L111: Why were these 13 ice rises selected from 30 ice rises (L109)? Is it based on the size of the ice rises? Please clarify.*
    a. Thank you for this question, we will clarify this in the revised manuscript. From the full Matsuoka et al. (2015) inventory of ~30 coastal WAIS ice rises, we selected the 13 sites based on three criteria. First, we applied a minimum total area threshold, Dean Island (~699 km²) is the smallest included site, to ensure sites are large enough to sustain a stable summit divide over the timescales relevant to paleoclimate reconstruction (millennia). Second, we required sufficient elevation above the surrounding ice shelf to ensure the ice rise developed independent flow divides with slow horizontal ice flow (which is necessary for

undisturbed stratigraphic layer preservation and ice core paleoclimate reconstruction). Also, adiabatic cooling dictates that ice rise summits elevated several hundred meters above sea level will be several degrees Celsius cooler and thus less likely to experience significant surface melting than surrounding ice shelves (the shortest ice rise is Dean at 397 m). Third, we selected sites to span the full longitudinal range of coastal WAIS (~91°W to ~162°W), since one aim of the study is to characterize how climate controls on snowfall vary across this sector. We have added these sentences to Section 2.1 to clarify these selection criteria.

3. *L37: What does "considerable (poorly observed)" indicate? Maybe contradicting to L36.*
    a. We agree that this may seem contradictory. We have revised Line 37 to: "…in addition to substantial spatial and interannual variability that remains poorly constrained due to the scarcity of direct observations in coastal West Antarctica."

4. *L150: "steig box" is not a frequently used word. Maybe changed to "S12 box" or relevant in this article. In addition, Steig et al., (2012) proposed the box as an indicator of U-wind but not analyzed V-wind, so there seems to be limited reason to analyze the V-wind and discuss its relationship with Steig et al., (2012).*
    a. Thank you, we have renamed this domain to the "S12 box" throughout the manuscript. Regarding the V-wind analysis, the reviewer is correct that Steig et al. (2012) defined this domain specifically in the context of zonal wind anomalies linked to CDW upwelling. We have revised Section 3.1.2 to clearly separate the S12-box U-wind discussion (which follows the Steig et al., 2012 framework) from the V-wind analysis (which addresses broader meridional transport questions brought up by studies in the intervening decade since S12, like O'Connor et al., 2025). We have removed any implication that V-wind results within the S12 box are directly connected to the CDW upwelling context established by Steig et al. (2012).

5. *Table 1: unit [degC] missing in temperature. And please clarify the unit of precipitation, [freshwater mm/a, or ice mm/a].*
    a. Thank you for this suggestion. We have added °C to the temperature column header and specified precipitation as m w.e. yr^{-1} (meters water equivalent per year) in the Table 1 caption.

6. *Figure 1 caption: [1] What does "remaining" ice core sites really means? Does it mean the site is not drilled yet? Please clarify. [2] Please clarify that red dots indicate "existing" or "previous" ice core sites (if I understand correctly).*
    a. We agree with this clarification and have revised the Figure 1 caption to: "…red dots indicate ice rise locations where ice cores have previously been recovered; orange dots indicate previously drilled ice core sites at non-ice-rise WAIS

    locations; and blue dots indicate previously drilled ice core sites at Antarctic Peninsula and East Antarctic Ice Sheet locations.” This removes the ambiguous term “remaining” and clarifies the status of each category.

7. *Figure 4: sentences “To reconstruct…” are unnecessary in this figure caption.*
    a. Thank you, we have moved the interpretive guidance from the Figure 4 caption into the main body of Section 3.1.2, condensing the caption to focus on describing the figure content. The interpretive text is retained in the manuscript, as it directly serves the applied site-selection purpose of the paper.

8. *Figures 4, 5, 7, 8: Bottom figure panel showing climate index locations can be unnecessary (figure caption is sufficient).*
    a. Thank you for this suggestion; however, we kept the bottom panels for Figures 4,5,7, and 8 because they contain the red boxes which define the regions that the correlating variables are averaged over.

9. *Figures A1-A4, I don't understand why A1-A4 are necessary in this research article, because the figures seem to present a summary of previous research. Also, the caption lacks the information of red dots.*
    a. We agree and have removed Figures A1–A4.

10. *Data availability: The data used in B1 and B2 (the SAM index and the ENSO index) can be specified.*
    a. Thank you for noting this. We have updated the Data Availability section to specify: (1) the Marshall (2003) SAM index used for Figure B1 validation is available from the British Antarctic Survey at https://legacy.bas.ac.uk/met/gjma/sam.html; (2) the observed Niño 3.4 index used for Figure B2 validation is from the NCAR Climate Data Guide (Trenberth et al., 2025); and (3) ERA5-derived fields are available through the Copernicus Climate Data Store (doi:10.24381/cds.adbb2d47).

References for new citations:

1. Lenaerts, J. T. M., Medley, B., van den Broeke, M. R., and Wouters, B.: Observing and modeling ice sheet surface mass balance, Reviews of Geophysics, 57, 376–420, https://doi.org/10.1029/2018RG000622, 2019.

2. Lenaerts, J. T. M. and van den Broeke, M. R.: Modeling drifting snow in Antarctica with a regional climate model: 2. Results, J. Geophys. Res., 117, D05109, https://doi.org/10.1029/2010JD015419, 2012.

3. Lenaerts, J. T. M., van den Broeke, M. R., Déry, S. J., van Meijgaard, E., van de Berg, W. J., Palm, S. P., and Sanz Rodrigo, J.: Modeling drifting snow in Antarctica with a regional climate model: 1. Methods and model evaluation, J. Geophys. Res., 117, D05108, https://doi.org/10.1029/2011JD016145, 2012a.

4. Lenaerts, J. T. M., van den Broeke, M. R., van de Berg, W. J., van Meijgaard, E., and Kuipers Munneke, P.: A new, high-resolution surface mass balance map of Antarctica (1979–2010) based on regional atmospheric climate modeling, Geophys. Res. Lett., 39, L04501, https://doi.org/10.1029/2011GL050713, 2012b.

5. Lenaerts, J. T. M., Ligtenberg, S. R. M., Medley, B., van de Berg, W. J., Kuipers Munneke, P., van Meijgaard, E., van den Broeke, M. R., and Malles, J. H.: Climate and surface mass balance of coastal West Antarctica resolved by regional climate modelling, Ann. Glaciol., 59, 29–41, https://doi.org/10.1017/aog.2017.42, 2018.

6. Trusel, L. D., Frey, K. E., Das, S. B., Kuipers Munneke, P., and van den Broeke, M. R.: Satellite-based estimates of Antarctic surface meltwater fluxes, Geophys. Res. Lett., 40, 6148–6153, https://doi.org/10.1002/2013GL058138, 2013.

7. Kingslake, J., Ely, J. C., Das, I., and Bell, R. E.: Widespread movement of meltwater onto and across Antarctic ice shelves, Nature, 544, 349–352, https://doi.org/10.1038/nature22049, 2017.

8. Shepherd, A., Fricker, H. A., and Farrell, S. L.: Trends and connections across the Antarctic cryosphere, Nature, 558, 223–232, https://doi.org/10.1038/s41586-018-0171-6, 2018.