Reviewer 1

SUMMARY

The study presents the impact that different ENSO-induced atmospheric circulation changes have on Antarctic ice sheet mass changes and analyze teleconnections with the southern annular mode. The authors show that there is strong event-to-event spatial variability between ENSO events using GRACE observed mass changes, regional climate model output and ERA5. This work fits well within the scope of the journal and provides a contribution to the field. The manuscript is generally well written, but some paragraphs can be somewhat lengthy. The following comments should help with solving the remaining issues before publication, with e.g. L1 referring to line 1.

Author's response: We thank you for your thoughtful and constructive comments, which have contributed to improving the clarity, structure, and scientific integrity of the manuscript. All major and minor points have been carefully addressed.

General comments:

Reviewer comment

- Recently, a new version of the regional climate model RACMO2.4p1 was published for the Antarctic ice sheet (Van Dalum et al., 2025, https://doi.org/10.5194/egusphere-2024-3728), which includes new physics (in particular relevant here are changes in precipitation). Importantly, RACMO2.4p1 also has a higher horizontal resolution of 11 km compared to the 27 km resolution used in RACMO2.3p2. Using the SMB of RACMO2.4p1 would improve the comparisons done in this study and I suggest the authors to use this version instead of RACMO2.3p2. RACMO2.4p1 data can be found here: https://doi.org/10.5281/zenodo.14217231

Author's response: In this study, we are primarily interested in the broad patterns associated with ENSO and the impact of the update of RACMO needs exploration. We will examine the differences produced by RACMO2.4p1 and, if they are substantial, we will update the results. If they are not, we will make note of their similarity.

Reviewer comment

- In the manuscript, basal melting is mentioned but SMB and mass changes are not studied on the ice shelves, hence relating the results to basal melting is difficult. Therefore, consider to include ice shelves in the comparison with RACMO SMB in e.g. Fig. 3b and elsewhere, and if possible also for GRACE, or explain why that cannot be done. Furthermore, it is also interesting to see how the SMB changes over the major ice shelves for each ENSO period.

Reviewer comment

Author's response: We did not examine basal melting in this study. However, as GRACE data cannot distinguish between mass changes due to atmospheric forcing and those due to ice dynamics, our mention of basal melting refers to components of ice mass change that are potentially not explained

by atmospheric processes. We will revise this section of the manuscript for better clarity and to avoid any confusion.

Reviewer comment

- I think it is valuable for this study to mention whether an ENSO event is central or eastern and discuss if and how such events differ, as it may explain some of the patterns that are identified in this study and therefore increase understanding. The authors shortly discuss the potential importance in the manuscript, like on L486-495, but I think a more in-depth analysis will improve the manuscript. Other work, like Macha et al. (2024), may provide information about whether an ENSO event is central or eastern, or it can be determined by following methods described by Ren and Jin (2011).

Author's response: The use of cumulatively summed ENSO indices allows us to capture the net influence of all ENSO events within a period, including transitions between central and eastern Pacific events. This means that our ENSO periods may cover a single ENSO event, or they may cover a series of events, such as two or three La Niña events in a 2-3 year period. Because of this, it is a different technique to that of Macha et al., as one of our 'ENSO events' may cover both central and eastern Pacific events. In addition the Niño3.4 index does not distinguish between central and eastern-type ENSO events, however we acknowledge the value of more detailed classification. We will expand our discussion of the Macha et al work. We agree that it would be helpful to indicate whether the El Niño–dominated periods included Central or Eastern Pacific events. Rather than assigning events on a month-by-month basis, we will refer to established classifications in the literature to identify which periods include Central or Eastern Pacific El Niño events. This will provide useful context without implying monthly resolution that our data do not support.

Reviewer comment

- Not all locations that are discussed in the manuscript are shown on a map, like the Wedell Sea, Ross Sea, location of the ASL or the various ocean sectors. Including the locations mentioned in the manuscript will improve clarity, making it easier to follow.

Author's response: As suggested, we will revise the manuscript to include more regional delineation on the maps, improving clarity and ease of interpretation.

Reviewer comment

- Including maps where the SMB changes are shown in percentage of the total SMB for the considered periods will help to understand how big the impact of ENSO/SAM is on the various regions that are considered, as some changes may seem large in for example high precipitation areas, while they are only relatively small. An alternative could be to report the integrated SMB values in Gt yr-1 for the ENSO events for the whole domain and smaller regions and compare them to the reference period.

Author's response: Since we are interested in the total mass of the ice sheet we are interested in both absolute and relative impacts. To address the relative impact, we will include maps showing SMB changes expressed as a percentage of the climatological mean SMB for each ENSO-dominated period. For each period (e.g., the 2009–2010 El Niño-dominated period), the mean SMB will be computed and compared to the long-term climatological mean at each grid point, then expressed as a percentage. These maps will highlight regions where ENSO-related atmospheric circulation changes

result in substantial deviations in SMB. However, our objective is to capture the absolute mass change rather than the relative mass change.

Specific comments:

Reviewer comment: L18: As you also use regional climate model output in your study, it should be mentioned in the abstract as well.

Author's response: We will include the model output in the next revised text.

Reviewer comment: L23-26: "… and its influence on the ASL and the Southern Ocean circulation can be equally (and in some cases more) important to AIS variability." Please specify with respect to what or rephrase this sentence.

Author's response: We will rephrase this sentence for better clarity.

Reviewer comment: Abstract: I think it is also important to shortly mention the uncertainties in the abstract that you also mention in the text, such as the relatively short time period that you use and the various teleconnections that may have not happened yet within this time period, or other processes like atmospheric rivers.

Author's response: We agree with the suggestion and will include it in the abstract.

Reviewer comment: L29-30: "The drivers of inter-annual to decadal Antarctic Ice Sheet (AIS) mass variability are complex and not yet fully understood". Please add a reference to this.

Author's response: Reference will be added to this statement in the revised manuscript

Reviewer comment: L35: Not only precipitation, but also riming can add to the SMB.

Author's response: We will revise the manuscript accordingly.

Reviewer comment: L43: Can you specify here what typically the time scale is that the SAM changes from positive to negative, or vice versa and why the SAM happens?

Author's response: We will elaborate on the timescale of the SAM changes and provide further explanation of the underlying mechanisms driving these variations.

Reviewer comment: L50: Is the total reduction of precipitation in the East AIS typically comparable to the precipitation increase in West Antarctica and the western Antarctic Peninsula? In other words, looking at the AIS as a whole, does a positive SAM increase or decrease the SMB?

Author's response: Overall, positive SAM phases are associated with a net reduction in SMB over the AIS, while negative SAM phases are linked to a net increase in SMB. We will revise this paragraph to more clearly reflect the overall impact of SAM on AIS SMB.

Reviewer comment: L67-75: Please add the location of the ASL, sectors like the Pacific sector, Indian sector etc. and other names in a map (for example in Fig. 2), which would help visualize the processes described the paper.

Author's response: We will include the mean locations of the ASL, as well as the Pacific, Atlantic, and Indian sectors, in Fig. 2 for clarity.

Reviewer comment: L76-83: Mention here why your study is different than the studies that you mention.

Author's response: We will clarify in the revised manuscript why this study is unique compared to previous studies, highlighting its novel contributions.

Reviewer comment: L87: As GRACE observes mass changes, the mass loss due to processes like runoff and sublimation are also included in the signal and should be mentioned here, even though they are relatively small compared to discharge.

Author's response: We will revise the manuscript as suggested.

Reviewer comment: L139: Please mention that the index is normalized in Fig. 1a.

Author's response: We will revise the manuscript as suggested.

Reviewer comment: L149: Also mention that the climate indices are detrended in Fig. 1c.

Author's response: We will revise the manuscript as suggested.

Reviewer comment: L155-161: Consider moving this paragraph such that it is mentioned before the paragraph of L148-154.

Author's response: We will revise the manuscript as suggested.

Reviewer comment: L162-164: "...where the positive phase of ENSO dominates the negative ENSO phase until a positive peak in the cumulative index is reached…". I think that I know what the authors mean, but consider reformulating this to improve clarity. Also, do you apply a minimum length that an ENSO period has to last?

Author's response: The sentence will be revised to improve clarity. We did not apply a minimum length criterion but were instead focused on the total mass change over the duration of each ENSO-dominated period.

Reviewer comment: Fig. 1: Please add a description to the Y-axis of the figures. In Figure 1.d, consider adding ENSO and in Figure 1.e SAM in the top of the figure, which would help reading the figure more quickly.

Author's response: We will revise the manuscript as suggested.

Reviewer comment: Section 2.3: It has not been mentioned in the paper before why you want to use a regional climate model and why it is necessary, which should be explained in e.g. the introduction before explaining what regional climate model you are going to use.

Author's response: A brief explanation of the rationale for using a regional climate model will be included in the revised manuscript.

Reviewer comment: L189: ."..at its lateral and ocean boundaries…" → at its lateral boundaries and SST and sea ice extent at the sea surface boundary…

Author's response: We will revise the manuscript as suggested.

Reviewer comment: Section 2.4: The authors should mention here why it is necessary to use ERA5 over RACMO output for the 10 m wind speeds and sea level pressure.

Author's response: We will provide a justification for using ERA5 instead of RACMO output for the wind and sea level pressure fields in the revised manuscript.

Reviewer comment: L225: Capital letter is missing in 'key'.

Author's response: We will revise the manuscript as suggested.

Reviewer comment: L227-229: Also mention here that you plot ERA5 and RACMO in Figure 3.

Author's response: We will revise the manuscript as suggested.

Reviewer comment: Fig. 3: I do not fully understand what is shown here. Is this the SLP and winds, SMB and GRACE mass loss averaged over the ENSO events? If this is the average over the ENSO events, including both El Nino and La Nina, would they not compensate each other?

Author's response: We will reword the methods section and corresponding figure captions to improve clarity, and we will take special care to ensure consistent and precise use of terminology throughout the manuscript. The figure shows the regression coefficient of sea level pressure (SLP) and winds anomalies (cumulatively summed), surface mass balance (SMB, cumulatively summed), and GRACE anomalies onto the cumulatively summed ENSO index. The results illustrate the atmospheric and mass patterns associated with El Niño events; conversely, the opposite pattern is generally observed during La Niña conditions. We will review the description and improve the clarity

Reviewer comment: Regarding Figures 4 and 5, we agree that interpreting the results would be easier with additional context on the SAM phase. We will revise the figure captions and/or figure panels to indicate whether the SAM index during each ENSO event was positive, negative, or neutral. This will help clarify how the combined phase of ENSO and SAM influences the observed spatial patterns.

Author's response: The manuscript will be amended accordingly.

Reviewer comment: Fig. 4i-l: Do you know why the north-south striping is so much more pronounced in Fig. 4j and Fig. 4l compared to Fig. 4i and Fig. 4k?

Author's response: It is possible that the north-south stripping is much more pronounced over shorter periods of time. Furthermore, due to instrument degradation toward the end of the GRACE mission, the observational error increases, which likely contributes to the more noticeable north–south striping in Fig. 4j and Fig. 4l.

Reviewer comment: L310: Do you mean Fig. 4g instead of Fig. 4c?

Author's response: Fig. 4c instead.

Reviewer comment: L311-312: "Note that the 2002-2005 SMB anomaly is only marginally positive (Fig. 4a)." → Note that the 2002-2005 SMB anomaly is only marginally positive for the Antarctic Peninsula (Fig. 4e).

Author's response: We will revise the manuscript as suggested.

Reviewer comment: L313, 314: Fig. 4f → Fig 4f, h and also Fig. 4j → Fig. 4j, l.

Author's response: We will revise the manuscript as suggested.

Reviewer comment: L323: Please also show these sectors on a map, e.g. Fig. 2.

Author's response: We will revise the manuscript as suggested.

Reviewer comment: L330-353: Link the pressure anomalies and wind changes to moisture transport and their consequent impact on SMB and mass changes. These paragraphs can also be shortened.

Author's response: The paragraphs will be rewritten for clarity and improved flow.

Reviewer comment: L380-381: Fig. 5f, g-h → Fig 5f-h and also Fig. 5j, k-l → Fig. 5j-l

Author's response: We will revise the manuscript as suggested.

Reviewer comment: L385-387: Can you explain more how the northerly winds from the Pacific and southerly winds from the continent can lead to convection? And how it may result in positive mass anomalies?

Author's response: We attribute the positive mass anomalies to the convergence zone formed where northerly and southerly winds meet, enhancing convection and leading to increased precipitation.

Reviewer comment: L393-398: Similarly, as before, link the pressure and wind anomalies to moisture transport and then to SMB and mass changes.

Author's response: We will revise the manuscript as suggested.

Reviewer comment: L421-426: How much of the 2020-2022 La Nina SMB signal is caused by this atmospheric river event? Is it possible that it is (almost) completely dominated by it?

Author's response: This was not included in our initial analysis, but we will incorporate an assessment to determine the extent to which the March 2022 ice mass anomaly influenced the 2020–2022 La Niña-dominated period.

Reviewer comment: Fig. 6: How did you calculate the average of the anomalies shown here? Did you weigh them by the length of the El Nino or La Nina-dominated periods? Or did you simply take the average of the maps that you have shown in Fig. 4 and 5?

Author's response: We simply averaged the anomaly maps presented in Figures 4 and 5 without weighting by period length. Our aim was to highlight the mean spatial response of ENSO. We will clarify this in the figure caption and in the results section and note it in discussion.

Reviewer comment: 459-461: Can you elaborate about these unusual climate dynamics? Does this have any impact on ENSO/SAM related SMB changes that you have discussed in the paper?

Author's response: We will expand on the unusual climate dynamics and explain how they influence the observed ENSO/SAM-related SMB variability. This will be included in the revised manuscript to provide a clearer context for the observed mass change anomalies.

Reviewer comment: L474-476: I am not sure if I fully understand how your results support the findings that increased basal melt is compensated by higher SMB. If I am not mistaken, you do not include ice shelves in your analysis where basal melt can occur, so how do you know that the positive SMB anomalies and increased mass that you show compensate for increased basal melt?

Author's response: We agree with your comment, and this statement will be omitted in the revised manuscript.

Reviewer comment: L477: "… El Nino-dominated period in the Amundsen sector differ" → "… El Nino-dominated periods in the Amundsen sector differs"

Author's response: We will revise the manuscript as suggested.

Reviewer comment: L483-485: As you include the complete events, doesn't it make your methods more vulnerable for irregular events, such as atmospheric rivers, that may overshadow the ENSO signals?

Author's response: Our methodology is vulnerable to irregular events such as atmospheric rivers (ARs). However, we can't exclude ARs from the methodology (there are multiple each year), but we can provide additional context and strengthen the discussion the likely contribution of ARs to SMB anomalies during ENSO dominating periods, using some key examples (e.g. 2009 in DML and 2022 in Wilkes Land) from the ENSO-dominated period by accounting the proportion of the signal to that AR. We will ensure that our discussion remains measured and is clearly framed within the context of Shields et al. (2022) and related work.

Reviewer comment: L508-510: Considering moving this to the la nina part.

Author's response: We will revise the manuscript as suggested.

Reviewer comment: L524: "tie" → "tied"

Author's response: We will revise the manuscript as suggested.

Reviewer comment: L550-551: "ENSO impacts West Antarctica through modulation of the ASL via Rossby wave propagation, though the ASL's influence on East Antarctica remains unclear", please add a reference to this.

Author's response: Reference will be added to this statement.

Reviewer comment: L583-585: Consider reformulating this sentence.

Author's response: We will revise the manuscript as suggested.

Reviewer comment: L595: The reference to Fig. 1c seems to be larger than the surrounding text.

Author's response: We will revise the manuscript as suggested.

Reviewer comment: L631: "However, the timescale of the response of the upstream ice to the positive SAM forcing is unclear and would involve a substantial lag". Please also describe how substantial this lag is what it would mean to the GRACE signal that you have used in this study.

Author's response: We will revise the manuscript to include a brief discussion of the potential lag in the response of upstream ice to positive SAM forcing. This lag, which may range from months to several years depending on regional ice dynamics, suggests that the GRACE signal may reflect a delayed response rather than an immediate reaction to SAM variability. We will clarify this point to help interpret the relationship between SAM and GRACE-derived mass changes more accurately.

Reviewer comment: L649: "This dynamical signal is stronger in West than in East Antarctica.". Add a citation to this.

Author's response: We will revise the manuscript as suggested.

Reviewer comment: L 658-659: The authors should add the time period that is considered in this study here. Also mention that you used ERA5 and RACMO.

Author's response: We will revise the manuscript as suggested.

Reviewer comment: L676-683: As it is the last concluding paragraph of the paper, remove references to figures and citations in this paragraph.

Author's response: We will revise the manuscript as suggested.

Reviewer comment: L676-683: Similar to my comment about the abstract, consider to shortly mention the uncertainties that have been discussed, such as the relatively short time period that you use and the various teleconnections that may have not happened yet within this time period, or other processes like atmospheric rivers.

Author's response: We will include it in the conclusion.

Reviewer comment: L690: This citation does not lead to the correct RACMO2.3p2 SMB data, as it refers to a newer version of RACMO: RACMO2.3p3.

Author's response: We will make the necessary correction.