

RC 2.

SUMMARY

“The changing mass of the Antarctic Ice Sheet during ENSO-dominated periods in the GRACE era (2002-2022)” presents a comprehensive analysis of the circulation, surface mass balance, and ice mass variation patterns associated during four different periods of El Nino and La Nina phases of ENSO over two decades. The study ties together a number of prior studies on how ENSO impacts Antarctic surface mass balance by highlighting that the spatial impacts of this mode of variability vary strongly depending on the periods considered. It brings together observational, reanalysis, and model datasets to produce a compelling argument that the ENSO signal in Antarctica is dependent on event-specific atmospheric circulation patterns. I look forward to the publication of this manuscript; however, I have some major comments about the presentation of results without indications of statistical significance, the structure of the results, and the wording around association versus causation when establishing the occurrence of circulation and SMB/mass variability patterns during periods of El Nino and La Nina. Please see major and minor comments below.

Author’s response: We appreciate your constructive feedback and believe that your suggestions will significantly enhance the clarity and scientific rigor of our study. We have carefully addressed each of the major and minor comments you raised.

MAJOR COMMENTS

Reviewer comment:

Statistical significance of trends and anomalies – many of the figures and corresponding analyses in this manuscript describe trends and anomalies in circulation, surface mass balance, and short-term mass change of the Antarctic Ice Sheet. However, the figures and discussion are missing critical information on the statistical significance of the results shown. For example, Fig. 2 shows the linear trend in ice mass change based on GRACE data, and here it would be very useful to add hatching or another indicator of where the trend is statistically significant. For Fig. 3, does the regression output p-values? If so, this would be another example of where it would be important to show where the statistically significant regions are. Same for Fig. 4 and 5 - for the composite maps, it would be key to add an indication for where the mean anomaly in sea level pressure is statistically significant (or exceeds the standard deviation among the different anomalies, for example). Without an indication on the maps for which regions exhibit statistically significant anomalies, readers cannot know which patterns are robust.

Author’s response: We agree with the reviewer that indicating statistical significance is important for a robust interpretation of our results. We are currently implementing statistical significance tests for the trends and anomalies presented in the manuscript. Significant regions will be highlighted on the maps to help readers identify which observed patterns are robust.

Reviewer comment

For the analyses of figure 4 and 5, I recommend structuring the text either by region (then compare different periods) or by period (and go through each region). The current structure of the text alternates between period and region, and that makes it hard to follow.

Author's response: We will also restructure the text to enhance flow and readability, following your suggestion to present each region individually before making comparisons across regions.

Reviewer comment

There are several instances of language that implies causation rather than correlation throughout the paper. For example on L229, “the results show that ENSO influences circulation over Antarctica, driving short-term fluctuation in AIS mass...” – rather, the results show that ENSO periods are correlated with certain meridionally-oriented circulation patterns conducive to the flow of marine air masses onto the AIS. Furthermore, since there is not an analysis of the individual events that are contributing precipitation during the time periods in question, I would avoid using the word “driving” when it comes of the ENSO phase/circulation pattern and the associated SMB signals. As mentioned later in the text, precipitation can be driven by a few impactful events or many smaller snowfall events, or a mix of the two, and this study does not address the link between individual snowfall events and the large-scale circulation patterns. Furthermore, some of the language such as “that weakened the Antarctic high” or “a developing low-pressure system” or “leading to...” implies that this study examined the time-evolution of sea level pressure anomalies during the periods in question. My understanding of the methods is that this was not done – in which case, I would strongly recommend to the authors to remove any suggestions of the temporal evolution of anomalies throughout the text, unless there are figures to back up the claims.

Author's response: Regarding the language used, we will refine it to avoid implying causation or temporal evolution that is not supported by our methods. Although much of this language was revised in earlier drafts, we acknowledge that some instances still remain. We will carefully review the manuscript to ensure that all wording clearly reflects correlation rather than causation and avoids terms that may suggest otherwise.

Reviewer comment

L421-426 – I would be careful presenting the March 2022 event here as if it were the only extreme event/atmospheric river that occurred here over the time period studied. Certainly, this event was a standout and had a huge impact on the surface. At the same time, there are multiple atmospheric rivers impacting each location along the Antarctic coastline every year – meaning that there is the opportunity to assess the relationship between extremes, ENSO, and SAM. I would encourage the authors to discuss their results in the context of Shields et al. 2022 (<https://agupubs.onlinelibrary.wiley.com/doi/full/10.1029/2022GL099577>) – which examined the associated between different modes of variability and atmospheric river occurrence and precipitation. Please see Fig. 3 of the Shields paper in reference to L565-566 of the Discussion as well – which shows the correlation between atmospheric river days and negative SAM.

Author's response: We will ensure that our discussion remains measured and is clearly framed within the context of Shields et al. (2022) and related work.

MINOR COMMENTS

Reviewer comment: Abstract – would recommend removing/reducing the number of acronyms, including AIS, ASL, SAM, and SST.

Author's response: We will reduce the number of acronyms used throughout the manuscript for improved readability.

Reviewer comment: L17 – "... we investigate AIS mass variability" (add mass? Same for L26)

Author's response: Mass will be added to this line.

Reviewer comment: L22 – "anticyclonic circulation anomalies" (add circulation)

Author's response: We will add the term "circulation" as suggested.

Reviewer comment: L23-26 – sentence is a bit confusing, consider shortening or clarifying

Author's response: The sentence will be rewritten to improve clarity.

Reviewer comment: L27 – what does "event-scale" mean? Synoptic-scale?

Author's response: In this instance, "event-scale" refers to synoptic-scale events. We recognize that the term "event-scale" may cause confusion given our use of the term "ENSO events" elsewhere in the manuscript. To avoid ambiguity, we will revise the text and change it to "synoptic-scale".

Reviewer comment: L43 – Add "The" to beginning of sentence, and "is regionally dependent and affects different regions" is redundant

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

Reviewer comment: L57 – it may be helpful to mention Pacific South American mode 1 (PSA1) in the Introduction, since this is another term used to describe the second most-dominant mode of variability around Antarctica, associated with ENSO.

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

Reviewer comment: L65 – impact of ASL on East Antarctica – is there any evidence that the ASL influences East Antarctic circulation? This is also mentioned at the end of the manuscript, and I think it would be helpful to clarify (a) whether any links have been found between the ASL and East Antarctic circulation (to support the statement that "the impact" exists) and (b) what those links could be.

Author's response: There is no clear evidence of a direct ASL impact in East Antarctica; however, it is possible that the ASL indirectly influences the region. Our analysis of the 2020–2022 La Niña period suggests that the ASL may have contributed to moisture inflow into Dronning Maud Land. We will revise the text to clarify this point and include supporting references, as suggested.

Reviewer comment: L73 – "reducing precipitation and SMB in West Antarctica" – please be specific about which regions of West Antarctica

Author's response: Okay, we will revise the language to be more regionally specific to improve clarity and accuracy.

Reviewer comment: L84-105 – really nice summary here, framing the motivation for this study in the context of prior literature

Author's response: We thankful to the reviewer.

Reviewer comment: L112 – clarify what COST-G RL-01 V0003 50km is, and please add a discussion either here or in the Discussion section about the spatiotemporal resolution of GRACE observations.

How well do these observations capture spatial variability in accumulation? Is there a tendency to under/overestimate surface mass balance anomalies given the 300km resolution?

Author's response: We will expand the discussion of the GRACE dataset to include a description of its effective spatial resolution (~300 km) and the implications for detecting surface mass balance anomalies.

Reviewer comment: L128 – Is the linear trend sufficient for capturing ice mass variation over 2002–2022? Is the 7-month moving median specifically applied for the linear trend removal, or do all results shown include the 7-month-averaged signals? Are there regions where the trend is/isn't statistically significant, by grid point? Is the trend removed everywhere or only where it is significant?

Author's response: A 7-month moving median is used to smooth the GRACE data before computing the ice mass variation trend over the period 2002–2022. No significance test was conducted, but it will be included in our future analysis. The results for ENSO-dominated periods include the 7-month moving median signals, which are then detrended to focus on variability. The choice of a 7 month filter follows King et al. 2023 and is a subjective choice to dampen GRACE month-to-month noise only.

Reviewer comment: L132 – do you know if there is a lag between the initiation of an El Nino or La Nina event and the teleconnection that impacts Antarctic surface mass balance? Do you know the timescale of the teleconnection?

Author's response: King et al 2003 looked at it and we can't resolve it with our method as it is likely ~6 months.

Reviewer comment: Fig. 1 – “shows the cumulatively summed normalised raw indices after which it is renormalized” – I'm having a hard time understanding what the method is.

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.

Reviewer comment: Fig. 1 – please clarify what metrics were used to determine the ENSO phases shaded in (d) and (e). Also, I would recommend moving the legend from (c) to (a) and because there is no text labeling the figure axes, I'd recommend adding titles to each figure.

Author's response: We will revise the manuscript according to the suggestion.

Reviewer comment: L211/212 – “relative strengthening” and “relative weakening”

Author's response: We will modify as suggested.

Reviewer comment: Fig. 3 – how was the regression of 10m wind anomalies performed? For *u* and *v* separately, or did you use the wind vectors? For detrending the variables, did you use a linear trend? I think it would be helpful to have more information on the methods used here.

Author's response: The regression was performed separately for the *u* and *v* components. Detrending was done by removing the linear trend. Additional information will be included.

Reviewer comment: L240 – It could be helpful to readers if you present some Antarctic Ice Sheet-integrated SMB values when discussing the precipitation anomalies during El Nino and La Nina.

Author's response: Okay, we will consider.

Reviewer comment: L242 – in Fig. 3, the W. Antarctic winds look more along-shore than onshore except over the Antarctic Peninsula – can you clarify? As a general comment, it is quite difficult to see the wind vectors along the Antarctic coast, meaning it's not always clear if/when a figure supports the conclusions in the text about wind directions at the coast.

Author's response: To address this comment, we will increase the size of the wind vectors in the figure to enhance visibility, particularly along the Antarctic coast. This adjustment will help clarify the wind patterns discussed in the text and more effectively support the conclusions presented.

Reviewer comment: L273 – for the different periods of El Nino events presented, it would perhaps be helpful as added context to know whether these events were central or eastern.

Author's response: 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: L274 – “representing a weakened an/or shifted ASL” rather than an actual high-pressure system” – how do you know? Do you have a figure to show this?

Author's response: We make this observation in reference to the climatology, which indicates a high-pressure system over Antarctica. This pattern is evident when we compute the climatology over the study period (2002–2022), although it is not shown in the manuscript.

Reviewer comment: L276 – “influencing meridional circulation, thus driving distinct spatial patterns in SMB” – could add a mention of “marine intrusions”/marine air masses here to link these two processes (the meridional circulation and the SMB)

Author's response: The manuscript will be revised to establish a clearer connection between the two processes.

Reviewer comment: L278 – “West Antarctica as two regions” – I'm very confused about what region is actually meant by the Amundsen Sea sector. Are you including all of Marie Byrd Land and the Ross coast in the Amundsen Sea? Where does the Bellingshausen fall? I would recommend adding region names to one of your early maps, and being very specific in your description of regional patterns.

Author's response: A more detailed map with additional regional labels will be included to allow for clearer and more specific descriptions of the regional patterns discussed in the text.

Reviewer comment: L280 – “different signs but broadly uniform” – I am slightly confused by the wording in this sentence

Author's response: The sentence will be restructured for better clarity.

Reviewer comment: L286 – “influences” – please use language of association and not causation

Author's response: We will review the manuscript carefully to ensure the language is precise and does not imply causation where only correlation is observed.

Reviewer comment: L296 – “... over the continent that weakened the Antarctic high” – again, use “associated with a weakened Antarctic high” or similar

Author's response: We will review the manuscript carefully to ensure the language is precise and does not imply causation where only correlation is observed.

Reviewer comment: L298 – “observed positive anomalies” – from GRACE?

Author's response: We will clarify the observed positive anomalies.

Reviewer comment: L298 – “A low-pressure anomaly” – I see a low-pressure anomaly all along the coast, but not specifically between these two sites?

Author's response: We will clarify the position of the low-pressure anomaly.

Reviewer comment: L301-307 – do you have a hypothesis for why this pattern occurred? Other modes of variability and/or teleconnections?

Author's response: Again, we will clarify why this pattern occurred and the potential hypothesis. Our hypothesis is linked to that El Nino dominating period coinciding with a central Pacific El Nino event.

Reviewer comment: L308 – “two distinct mass variability responses” – I've seen this wording several times in the text and there are only two possible responses, right? Mass gain or loss? Please clarify.

Author's response: We agree with the reviewer that there are fundamentally two possible responses—mass gain or mass loss. We will revise the wording throughout the manuscript to clarify this and avoid ambiguous phrasing such as “two distinct mass variability responses.”

Reviewer comment: L327 – “western Dronning Maud Land” – please be specific about the region, and label on a map

Author's response: We will revise as suggested.

Reviewer comment: L333 – “southerly wind flow” and “northerly winds” – these are wind anomalies, right? If so, please refer to them as anomalies throughout the text. Also, these wind vectors are very hard to see in the figure. Perhaps I am misunderstanding the text, but I find it a bit confusing regarding the generating of “northerly winds into western regions, supporting slight positive anomalies”. I expect northerly winds to occur on the eastern flank of the low-pressure anomaly and I also see a convergence of northerly and southerly winds at the coast.

Author's response: The winds described here are wind anomalies and will be consistently referred to as anomalies throughout the text in a revised document. The wind vectors will be replotted and enlarged where possible to improve visibility for the reader.

We acknowledge the confusion and appreciate the reviewer's observation. The low-pressure anomaly is located further west of the Dronning Maud Land coast, and the northerly winds anomaly is on the eastern flank of the low-pressure anomaly. The convergence zone is more prominent toward Enderby Land, where a slight positive mass anomaly is observed. We will clarify this description in the text, and we expect the wind patterns to be more easily interpreted with the improved figure.

Reviewer comment: L339 – “central-eastern Dronning Maud Land”

Author's response: Agree, we will change it to central-eastern Dronning Maud Land.

Reviewer comment: L340 – “mid-latitude blocking pattern” – I would not necessarily call a high-pressure anomaly a mid-latitude block, without first looking at the mid-upper level geopotential height patterns and sea level pressure (not the anomaly).

Author’s response: We will revise the sentence to state that the feature resembles a mid-latitude block, but we have not explicitly categorized it as such.

Reviewer comment: L344-347 – this sentence is long and a bit confusing, recommend breaking it into two

Author’s response: The sentence will be break into two for more clarity.

Reviewer comment: L345 – 4c or 4b?

Author’s response: 4b. We will fix this.

Reviewer comment: L348 – I don’t know that I see mid-latitude westerlies in 4c? (also these are wind anomalies, right?) – maybe more like the polar jet?

Author’s response: These winds are anomalies, and the westerly jet observed primarily influences the AIS and the Southern Ocean, rather than the mid-latitudes as noted in the comment. It is more likely associated with the polar front jet. We will revise to indicate this.

Reviewer comment: L351 – “pressure anomalies” – specify low or high

Author’s response: A weak high-pressure anomaly over the continent. We will revise to...

Reviewer comment: L351 – “developing” implies time-evolution

Author’s response: The language will be revised to: “accompanied by a low-pressure anomaly in the adjacent ocean.”

Reviewer comment: Fig. 5 - I am slightly concerned that the striping in Fig. 5k, for example, which extends all the way from the interior to the coast (especially because the patterns exhibit spatial continuity). I would recommend to the authors that they mask out the interior region most affected by the striping.

Author’s response: We will take this into consideration and assess how to define the boundary of what should or should not be masked, in a way that does not obscure meaningful signals and is feasible to implement. If a suitable method can be identified, we will apply the masking. Otherwise, we will revise the figure caption to guide the reader’s attention toward the more robust signals along the coast.

Reviewer comment: L373 – “strengthening” – implies time-evolution

Author’s response: The language will be revised to: “reflecting an intensification and/or shift of the Amundsen Sea Low (ASL) (Fig. 5a–d).”

Reviewer comment: L378 – these low-pressure anomalies all look pretty elongated to me?

Author’s response: The statement will be deleted in the revised version.

Reviewer comment: L379 – “enhanced southerly wind anomalies” – in 5d, I see northeasterly onshore wind anomalies and positive SMB here in RACMO2?

Author's response: The focus was on the Amundsen Embayment, which led to the generalization of southerly wind anomalies. However, during our defined 2020–2022 La Niña-dominated period, the wind anomalies across the embayment are more northeasterly, potentially transporting moisture onshore—particularly along the western part of the embayment. This likely explains the positive SMB signal seen in the RACMO data. We will revise the manuscript to reflect this more accurate description.

Reviewer comment: L386 – “potentially can support convection and positive mass anomalies” – reference for this?

Author's response: The statement was a deduction intended to explain the observed positive mass anomaly. We will include a suitable reference to support this explanation in the revised manuscript.

Reviewer comment: L400 – again, here it would be very helpful to show what the regions of statistically significant positive/negative SMB are on the RACMO2 SMB maps.

Author's response: Statistical significance tests will be performed to define....

Reviewer comment: L409 – “resulting in uniform northerly winds and positive mass anomalies” – are you talking about the coast only? From the figure I see westerly and northwesterly winds, not purely northerly – though I would re-iterate that the wind vectors are so small in the maps that they are really hard to see. Finally, also mentioning once more that if these are wind anomalies they should always be referred to as such and not presented as if they were the actual wind field.

Author's response: As noted previously, the font size in the wind plots will be increased to improve the visibility of wind direction. The term “northerly wind anomalies” was used in reference to the coastal region; however, further inland the anomalies exhibit more westerly to northwesterly flow. We will revise the text to consistently refer to these as wind anomalies throughout.

Reviewer comment: L413 – “two distinct” – again, there are only two possible SMB responses, right?

Author's response: The current wording suggests a range of possibilities; however, there are only two possible outcomes. We will revise the text to more accurately reflect this conclusion.

Reviewer comment: L419 – “deepening” implies temporal evolution

Author's response: The language will be revised to: “due to the unusually deep low-pressure anomaly in the Pacific.”

Reviewer comment: L419–421 – these two features (low-pressure anomaly in the Pacific and wind anomalies over Wilkes Land) seem far apart spatially – I’m missing the connection here with respect to the circulation?

Author's response: The low-pressure anomaly appears to direct northwesterly winds toward Dronning Maud Land, rather than specifically over Wilkes Land. However, the co-occurrence of La Niña and a positive SAM phase seems to alter the atmospheric circulation pattern. Instead of the expected zonally symmetric flow over the Antarctic Ice Sheet (AIS), the circulation becomes more asymmetric, resulting in northerly to northwesterly wind anomalies over Wilkes Land. We will revise the paragraph to improve clarity and accurately reflect these circulations.

Reviewer comment: Fig. 6 – again, there needs to be information on the statistical significance of the patterns in this figure, which will presumably support the authors’ claims that different ENSO events are associated with different circulation and surface mass balance patterns.

Author's response: We agree with this suggestion and will perform a statistical significance test to support the conclusions presented in this study.

Reviewer comment: L430 – Amundsen Sea sector and Marie Byrd Land

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

Reviewer comment: L446-447 – language suggests causation

Author's response: The sentence will be rewritten to suggest a correlation rather than causation.

Reviewer comment: L453 – might help to remind readers what the bi-polar pattern is

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

Reviewer comment: L454 – what is meant by “underlying”? Most common, strongest, dominant?

Author's response: The “underlying” used here represent the dominant ENSO impact.

Reviewer comment: L470 – “coastal easterlies” – could you clarify this? I see coastal westerly wind anomalies in 4a, c, and d.

Author's response: There is weaken coastal easterlies (actual winds), which is shown by the observed coastal westerly wind anomalies.

Reviewer comment: L479 – western Ross Sea sector is not mentioned earlier in the text, nor is the Ross ice shelf shown in any figures. Could you clarify what is meant here?

Author's response: More geographical regions will be included and mention the manuscript going forward.

Reviewer comment: L490 – “the anomalous response can be attributed to altered Rossby wave propagation” – surely Rossby wave propagation influences almost all ENSO-associated circulation patterns around Antarctica?

Author's response: We will revise to clarify and highlight the differences in the propagation pathways of the Rossby waves during Central versus Eastern Pacific. Rossby wave propagation influences ENSO-associated circulation patterns around Antarctica. However, the source location of Rossby wave trains tends to be 20°–30° farther west during Central Pacific El Niño events compared to Eastern Pacific El Niño events. These differing propagation pathways result in a westward and latitudinal shift of the ASL during Central El Niño events relative to Eastern El Niño events.

Reviewer comment: L524 – “isolating ENSO signals” – I would be careful with stating that you are isolating ENSO signals here, because as was already mentioned, there are a number of different weather patterns and extremes that occurred during the periods over which the circulation and SMB patterns were composited.

Author's response: We will reword to prevent any potential confusion.

Reviewer comment: L525 – “convergence zone that enhances precipitation” – reference for this? And can you be specific about exactly where you see the convergence occurring? Do you see this in the actual wind fields too, not only the anomalies?

Author's response: References will be added, and the identified convergence zones will be cross-checked against the actual wind fields.

Reviewer comment: L4545-548 – reference?

Author's response: A reference will be added to support this statement.

Reviewer comment: L550 – “ASL’s influence on East Antarctica remains unclear” – as mentioned earlier, this implies that there is an influence but we don’t know what it is – is that the conclusion from Li et al. 2022, as cited?

Author's response: The influence of the ASL is primarily centred over West Antarctica but can also indirectly affect atmospheric circulation over East Antarctica. Zhang et al. (2021) analysed 500 hPa geopotential height anomalies during La Niña periods and suggested that the ASL facilitates moisture advection into East Antarctica. Similarly, our analysis of the 2020–2022 La Niña period shows a comparable pattern, with the ASL advecting north-westerly winds into Dronning Maud Land. Reference changed to Zhang et al. 2021.

Reviewer comment: L559 – can use “significant” if you show statistical significance of mass changes in the figure

Author's response: That was an incorrect use of the term 'significant' in this context.

Reviewer comment: L574-579 – it’s probably important to add there that it’s equally likely that certain modes of variability and their associated circulation patterns may be conducive to atmospheric river landfall in certain regions.

Author's response: We are in agreement with this suggestion and will incorporate it into the revised manuscript.

Reviewer comment: L598 – “structure of the westerlies was altered” implies causation, and refers to the winds rather than the wind anomalies.

Author's response: We will rephrase the wording to indicate a correlation rather than imply causation.

Reviewer comment: Discussion – general comment: this is a very long section, and while it is interesting, I think it comes across as somewhat redundant following the results and before the conclusion. I would recommend shortening it where possible, to make the section more concise and less repetitive.

Author's response: Thank you for the helpful suggestion. We agree that the Discussion section is a bit long and, at times, overlaps with the Results. We'll work on tightening the section to make it more concise and focused, while still capturing the key interpretations.