February 2025

Authors response to reviews on '*How do extreme ENSO events affect Antarctic surface mass balance?*' submitted to *The Cryosphere.*

Masashi Niwano
Editor, The Cryosphere

Thank you for considering our revised manuscript.

We are pleased that Anonymous Referee #1 is generally satisfied with our responses, with only two minor revisions remaining. We are also pleased the Editor has found our responses to Christoph Kittel (Referee #2) to be convincing. We thank Anonymous Referee #1 for their continued feedback, comments and suggestions which will further improve the manuscript.

Here, we provide responses to each of the reviewers' comments. Reviewer comments are in *italics.* Our responses are included in regular text. When noting our changes, we refer to both line numbers in the original manuscript and include wording changes in blue text and quotation marks (" ").

Jessica Macha and co-authors

Response to Reviewer 1:

General comments:
Comment: I appreciate the authors' great effort in improving the manuscript in response to my earlier comments. In particular, the careful writing and reserved attribution of the SMB anomaly to ENSO, taking other possibilities into account. The analysis of Rossby wave trains is also useful to identify where the differences originate. I still have two comments, of which the first one is important.

Response: We thank the reviewer for their constructive feedback and are glad that they appreciate the improved manuscript, including the clarification of reserved attribution, and the Rossby wave train analysis.

Specific Comments:
Comment 1a: Throughout the text, the authors use the term "impacts of El Niño". As the authors now agree, what is shown is not necessarily the impact of El Niño alone. It is the SMB anomaly during the El Niño event. For example, it says in the abstract (L.6) that "Regional impacts differ between individual events and cannot be generalized across all extreme events." More accurately, this should be "regional anomalies", rather than "regional impacts", as the causality is not demonstrated. I notice similar usage of "impacts" throughout the text. I suggest re-examining each use of the term "impacts".

Response: Yes, we agree that the use of "impacts of El Niño" is ambiguous as we have clarified that what is shown is not necessarily the impact of El Niño alone. Therefore as suggested we have re-examined the use of the term 'impacts' throughout the manuscript and reworded the following sentences (below):

Abstract L6: "Based on only three (five) events in the observational period, regional anomalies differ during the extreme El Niño (La Niña) events considered and cannot be generalised."

L56: "Overall, we aim to answer the following questions: do Antarctic SMB anomalies during extreme ENSO events follow a similar pattern? Where do these impacts occur? And more generally, do these extreme ENSO events also result in extreme Antarctic SMB changes?"

L107: "Non-extreme CP El Niño events (see section 2.1.3) are also included in our analysis, to provide a comparison to extreme El Niño events, building off Macha et al. (2024), which found that CP-type El Niño events result in widespread SMB increases in West Antarctica."

L109: "Moderate and strong El Niño events are also included in our analysis to allow comparison with El Niño events of lower magnitude."

L122: "In this study, we focus on ENSO in SON (of the year when the ENSO event develops), when the ENSO-Antarctic teleconnection is strongest"

L233: "Strong La Niña events induce a range of surface climate changes, with no clear pattern in common between strong La Niña events SLP, temperature, precipitation and SMB anomalies (Figure 4)."

L360: "Here, we have considered Antarctic SMB anomalies during extreme ENSO events in the historical record to determine if extreme ENSO events are associated with extreme SMB changes in Antarctica."

L365: "However, beyond the 2015/16 event and Enderby Land, our results show that extreme changes in Antarctic climate and SMB do not occur during extreme ENSO events."

Section 4.1 title: "Extreme ENSO events and moderate ENSO events"

L393: " However these results are not consistent across all three extreme El Niño events studied (other than in Enderby Land)."

L395: "Conversely, numerous other catchments exhibit similar SMB responses when extreme and moderate El Niño event SMB changes are compared. That is, the SMB changes during extreme ENSO events do not differ from those during moderate events

in Dronning Maud Land, Lambert-Amery system, Princess Elizabeth Land, Aurora Subglacial Basin, West Graham Land, Larsen, Filchner and Coats catchments."

L449: "Our findings further show that the 2015/16 event stands out relative to previous events, and is associated with more widespread and significant Antarctic SMB changes than during other extreme ENSO events."

L458: "This magnitude difference was partially attributed to the 2015/16 event being initiated from a warmer tropical Pacific background state than the 1982/83 and 1997/98 events (Santoso et al., 2017), resulting in the higher magnitude and more widespread anomalies in Antarctica."

L464: "Attributing whether there is an anthropogenic signal in these extreme ENSO events and SMB anomalies is beyond the scope of this study and requires centennial scale datasets to fully characterise ENSO variability (Stevenson et al., 2010)."

L488: "Our analysis of Antarctic surface mass balance during extreme ENSO events is limited by the length of the datasets available."

Comment 1b: While I partially understand the authors' intention, I think the following statements are too strong and can be misleading: "The impacts of extreme El Niño events in Antarctica therefore cannot be generalised; the extreme El Niño composite results miss key regional differences in impacts during events (Figure 3a-d). Extreme El Niño event impacts therefore need to be compared on a case-by-case basis."

By these statements, the authors implicitly attribute the observed anomalies to the extreme El Niño events. As the authors now carefully phrased in places throughout the text, the differences are not attributable to El Niño alone. Therefore, there is no evidence that "El Niño event impacts need to be compared on a case-by-case basis".

The composite analysis (or arithmetic average) is a powerful statistical tool to generalize the phenomena but has little meaning with a few samples. I think "The impacts of extreme El Niño events in Antarctica" can "be generalized" if there are enough samples. This is not what we have learned from this study but is supported by the textbook. Therefore, there is no convincing evidence that "The impacts of extreme El Niño events in Antarctica therefore cannot be generalized".

I also disagree with the point written in the response that "a key finding of our analysis is that the composite analysis cannot be used to generalize the behaviour of extreme El Nino or La Nina events." This is not necessarily a finding from this study but may be a statistical limitation.

It is safe to argue that the individual extreme events are statistically different from the baseline (because that is what the extremes are), but it is difficult to make a statistical statement about commonality or dis-commonality among the three samples. In my

opinion, this is a very valuable study consisting of three individual cases, but not more than that.

Response: We thank the reviewer for raising this point. We agree that the statements highlighted are too strong in wording, and implicitly attribute the observed anomalies to the extreme El Niño events. We also agree that the three individual extreme events are statistically different from the baseline, and that our findings do not extend further than these individual events. We therefore have reworded these points in the manuscript, as follows:

Abstract, L6: "Based on only three (five) events in the observational period, regional anomalies differ during the extreme El Niño (La Niña) events considered and cannot be generalised."

L229: "Changes in SLP, temperature, precipitation and SMB across Antarctica are not consistent between the 1982/83, 1997/98 and 2015/16 events, with regional differences in the magnitude and sign of anomalies (Figure 3e-p). The composite of extreme El Niño events also appears to miss key regional differences between events; however, this may be related to the small number of events in the analysis period (Figure 3a-d). Given this limitation, in this study we compare extreme El Niño events on a case-by-case basis to ensure that differences between events are adequately accounted for."

L254: "There are few similarities between surface climate anomalies, including SLP, surface temperature, precipitation and SMB during strong La Niña events (Figure 4e-x). The composite of strong La Niña events also appears to miss regional differences in the sign and magnitude of climate anomalies during individual events (Figure 4a-d). As for the El Niño composites, this may be due to statistical limitations associated with the small number of events considered. When conducting extreme ENSO event analysis in this study, each event and its impacts are assessed, to ensure key differences between events or impacts are not overlooked."

L316: "At the catchment scale, we find that SMB responses vary greatly between individual extreme ENSO events and that there are no consistent SMB responses between the three extreme El Niño events considered, except in Enderby Land, East Antarctica, where SMB anomalies are consistently positive (Figure 5)."

L354: "In summary, most SMB responses during the three extreme El Niño events identified are not significantly different from background and average conditions (Figure 6-7)."

Comment 1c: It is safe to argue that the individual extreme events are statistically different from the baseline (because that is what the extremes are), but it is difficult to make a statistical statement about commonality or dis-commonality among the three samples. In my opinion, this is a very valuable study consisting of three individual cases, but not more than that.

Response: We thank the reviewer for raising this point. We agree that the individual extreme events are statistically different from the baseline.

Comment 2: Could the author check whether the following statement is accurate? "RACMO is more appropriate than ERA5 for addressing SMB impacts due to its finer spatial resolution…" The ERA5 dataset is provided at 0.25x0.25 resolution (not the same as the original numerical model resolution), and 0.25 degree is about 27 km at the equator (same as RACMO). If one goes to polar regions, the zonal resolution becomes much finer. This is the reason why I originally asked the author if RACMO has the advantage of simulating moisture transport in the polar region than ERA5.

Response: Thank you for highlighting this inaccuracy. The reviewer is correct, we have stated that RACMO is of finer spatial resolution than ERA5 which is inaccurate. However, as outlined in detail in Supplementary Text S1, there are extra processes included in RACMO that improve the representation of SMB, resulting in more accurate Antarctic simulations of SMB than utilising P-E in ERA5. We have updated this text to correct the inaccuracy around spatial resolution and highlight the content of Supplementary Text S1 more clearly.

L67-68: "RACMO is more appropriate than ERA5 for addressing SMB impacts due to its adaptation to the polar regions, including consideration of orographic effects, post-depositional processes and an updated surface mass balance scheme that includes a firn module (van Dalum et al. 2022). We include a more detailed discussion on the polar developments in RACMO2.3p3, and justification for its use over ERA5, in Supplementary Text S1."