Climatology and Surface Impacts of Atmospheric Rivers on West Antarctica

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REVIEWER COMMENT #4:

General comments

The manuscript by Maclennan et al. presents a study of atmospheric river events and their effects on the climatology and surface mass balance in West Antarctica. First, the MERRA-2 and ERA5 reanalysis products are used to quantify the frequency, trends, and large-scale effects of ARs on precipitation in the period 1980 to 2020. Then in-situ observations from weather stations at Thwaites Glacier are used to reconstruct accumulation and firn conditions during a series of AR events in 2020. Finally, the possible future effects of increasing AR intensity and frequency on surface conditions and surface mass balance in the areas are discussed.

The paper provides a good background of ARs in West Antarctica and their effects on surface mass balance, and the large-scale study is combined with the in-situ data into a very interesting discussion. The topic is timely and the paper is suitable for The Cryosphere.

The only minor issue is that the presentation of the work should more clearly state the goal of the investigations as well as summarize the findings more clearly. As I see it, the main strength and new contribution of this paper is that the authors combine the large-scale reanalysis products with detailed in-situ data. Thereby, they are able to qualify the discussion of the future impacts much more convincingly than from reanalysis products alone. This message should be communicated more clearly. The discussion section is strong, but I suggest that the Discussion and Conclusion section is divided into two, so there is a separate conclusion section in order to communicate the findings more clearly.

> **The authors would like to thank the reviewer for providing comments and feedback that help to improve the content and clarity of the manuscript. In response to comments about the goal of the investigations in the introduction (which are similar to feedback provided by the other two reviewers), we have revised the last two paragraphs of the introduction to place our work in the context of previous Antarctic AR studies, highlight the gap in the existing research, and note how our study provides a key link between large-scale AR patterns over West Antarctica and localized impacts over Thwaites Glacier. Similarly, we have revised the first paragraph of the discussions and conclusion to emphasize that the combination of observation and reanalyses enables us to discuss how AR impacts may become exacerbated in a future climate. We have decided to keep the discussion and conclusions section**

combined, because it enables us to integrate the most important findings of this study with a discussion on how our results relate to previous studies on Antarctic ARs and how they depend on our choice of methodology. Responses are written in bold, and excerpts from the manuscript are *italicized*. Changes to the text are *italicized and in blue*. Line numbers refer to track changes in the revised manuscript. Please see our responses to the comments below:

Detailed comments:

Page 1: the abstract is far too long. The length should be 250 words (see instruction in the TC). Remove sentences that are essential background or discussion.

The authors concur with this comment and we have reduced the length of the abstract to 250 words. Please see the revised abstract in lines 1-14 of the manuscript.

Page 2-3: The introduction contains the motivation and background on ARs. However, the purpose of the study is not clearly stated. Rewrite the last paragraph to start with "In this study, we… This would also make it clear from the start how this paper differs from earlier studies by including the in-situ data, and why these data are included.

We have rewritten the last paragraph of the introduction (line 70) to clarify the purpose of our study and how it addresses a knowledge gap in prior studies. The last paragraph has been rewritten as follows:

Despite the importance of ARs for WAIS SMB, the spatial variability of extreme precipitation associated with ARs over Antarctica is poorly understood. Previous research using a regional climate model showed coastal regions of the WAIS broadly experience 1-3 days of AR conditions per year which account for around 40% of extreme precipitation events from 1980 to 2020 (Wille et al., 2021). However, the low spatiotemporal resolution of atmospheric reanalysis products does not highlight the effects of topography or capture precipitation patterns during individual AR events (Gehring et al., 2022). In this study, we provide both a large-scale, climatological perspective of West Antarctic ARs and a focused case study of a particular AR event. First, we use atmospheric reanalyses to quantify the landfalls and accumulation impacts of ARs from 1980 to 2020 over Marie Byrd Land and the Amundsen Sea sector. Then, we use in-situ observations and a firn model to examine the specific impacts of a series of three successive ARs that made landfall on TG in February 2020, as well as the ability of reanalyses to reproduce those observations. Our analysis provides key indications of small-scale spatial variability in AR-driven accumulation and surface melting on TG, within the broader context of the climatology of ARs in the region. Finally, we discuss

> ***how ARs contribute to the present mass balance of the WAIS, which improves our understanding of how their impacts may change in future climate scenarios.***

Page 2:, line 33: I don’t think “TG” has been defined, please do so.

> **Thank you for pointing this out, we have revised the sentence to define TG as Thwaites Glacier (line 27):**
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> ***In particular, Thwaites Glacier (TG), which borders the Amundsen Sea, is at considerable risk for continued grounding line retreat in the future because it is grounded on inward sloping bedrock, which may lead to a rapid positive feedback for increasing ice flow and retreat, termed 'marine ice sheet instability' (Weertman, 1974; Schoof, 2012).***

Page 4: AMIGOS – include a reference to define what AMIGOS is, it is not enough to include it in the title of section 2.1

> **We have removed AMIGOS from the title of section 2.1 and renamed it "Observations from Automatic Weather Stations". In the first sentence of section 2.1, we introduce the AMIGOS as follows (line 85):**
>
> ***Through the Thwaites-Amundsen Regional Survey and Network Integrating Atmosphere-Ice-Ocean Processes (TARSAN) project of the International Thwaites Glacier Collaboration, automatic weather stations known as Automated Meteorology–Ice–Geophysics Observation System (AMIGOS, Scambos et al., 2013) were installed on Thwaites Eastern Ice Shelf at Cavity Camp (75.033 °S, 105.617 °W) and Channel Camp (75.050 °S, 105.4334 °W) during a field campaign in austral summer 2019/20 (Fig. 1).***

Page 4, line 100: add “s” to sensor, and change “is” to “was”.

> **We have revised the sentence to reflect that there were two sensors (plural) at 6 m above the surface during the event (line 95).**
>
> ***The AMIGOS temperature sensors were located about 6 m above the surface during the period of interest in this study, so we refer to AMIGOS air temperatures as "near-surface" when compared to 2 m air temperatures from MERRA-2 and ERA5.***

Page 5: Perhaps explain a little more clearly why you focus on the precipitation and use the vIVT algorithm to detect the ARs. The precipitation effect is most important at present, but this could perhaps be made more clear here, or stated earlier in the motivation.

We have added clarification in section 2.3 to emphasize why we use the vIVT algorithm to detect ARs (starting on line 137):

Wille et al. (2021) found that IWV is better suited for identifying ARs that cause surface melting, as high IWV over the AIS is associated with cloud development and high downwelling longwave radiation to the surface. Comparatively, the vIVT-based definition of ARs is better suited for studying snowfall, since the meridional transport of water vapor is linked to atmospheric dynamics that lead to precipitation.

In this study, we primarily focus on AR-driven precipitation, and thus we use the vIVT catalogues with AR detection at 3 hourly intervals based on MERRA-2 reanalysis.

We have also revised the last two paragraphs of the introduction to clarify the motivation for studying AR-driven precipitation, starting on line 58.

Page 7, figure 1: Indicate the 80degS latitude at the figure to the left. This would be helpful later in the discussion. What is the black outline in the middle figure?

We have added information on the 80 deg S boundary for AR detection to Fig. 2 in the paper, which shows results from the Wille et al. (2021) AR detection algorithm and marks the 80 deg S boundary with a grey mask. The figure caption for Fig. 2 has been revised as follows:

Grey shading over the interior of the ice sheet marks the 80 deg S boundary of the Wille et al. (2021) AR detection algorithm.

The black outline in the middle figure of Fig. 1 refers to the region of interest in this study. We have added it to the first sentence of the figure caption to improve clarity:

Map showing the region of interest in this study -- the Amundsen Sea Embayment and Marie Byrd Land in West Antarctica (outlined in black).

Page 10, line 231: Please define "ASE".

We have removed ASE (Amundsen Sea Embayment) from the sentence and replaced it with "Amundsen Sea sector" (line 238).

The geometry and orientation of TG render it highly susceptible to synoptic flow-induced snow storms caused by ocean air masses that are driven from the Southern Ocean into the ~~ASE~~ Amundsen Sea sector.

Page 12, line 278: remove "and".

Done (line 283).

MERRA-2 accumulation is 88 kg m^{-2}, ~~and~~ ERA5 accumulation is 87 kg m^{-2}.

Page 12, line 280: The spatial resolution of the reanalysis product could both mean that it does not resolve variations within the grid cell, and also that some larger scale patterns are not resolved properly. It could be relevant to mention both.

Sub-grid scale processes, including local snowfall over Thwaites Eastern Ice Shelf, may not be resolved by the reanalysis products used in this study. However, we are confident that the reanalysis is able to capture the synoptic-scale features of interest that we discuss in the paper. Previous studies including Turner et al. (2013) and Raphael et al. (2016) have used reanalyses to describe large-scale flow patterns in this region. Gorodetskaya et al. (2014), Pohl et al. (2021), and Turner et al. (2022) used reanalyses to examine the synoptic forcing of atmospheric rivers in other regions of Antarctica.

In section 2.2 we have added discussion on how the difference in spatial resolution between the reanalyses and observations means that the reanalyses may not resolve local weather at the AMIGOS sites (line 125):

While AMIGOS observations reflect local conditions at the Cavity and Channel Camp sites, MERRA-2 and ERA5 data represent grid-cell averages, meaning they may under- or over-estimate local values for temperature, surface pressure, wind speed and wind direction slightly when compared to the observations.

Gorodetskaya, I. V., Tsukernik, M., Claes, K., Ralph, M. F., Neff, W. D., and Van Lipzig, N. P. M. (2014): The role of atmospheric rivers in anomalous snow accumulation in East Antarctica, Geophysical Research Letters, doi: 10.1002/2014GL060881

Pohl, B., Favier, V., Wille, J., Udy, D. G., Vance, T. R., Pergaud, J., Dutrievoz, N., Blanchet, J., Kittel, C., Amory, C., Krinner, G., and Codron, F. (2021): Relationship Between Weather Regimes and Atmospheric Rivers in East Antarctica. Journal of Geophysical Research: Atmospheres, doi: 10.1029/2021JD035294

Raphael, M. N., Marshall, G. J., Turner, J., Fogt, R. L., Schneider, D., Dixon, D. A., Hosking, J. S., Jones, J. M., and Hobbs, W. R. (2016): The Amundsen Sea Low: Variability, Change, and Impact on Antarctic Climate. Bulletin of the American Meteorological Society, doi: 10.1175/BAMS-D-14-00018.1

Turner, J., Phillips, T., Hosking, J. S., Marshall, G. J., and Orr, A. (2013): The Amundsen Sea low. International Journal of Climatology, doi: 10.1002/joc.3558

Turner, J., Lu, H., King, J. C., Carpentier, S., Lazzara, M., Phillips, T., and Wille, J. (2022): An Extreme High Temperature Event in Coastal East Antarctica Associated With an Atmospheric River and Record Summer Downslope Winds. Geophysical Research Letters, doi: 10.1029/2021GL097108

Page 14, line 306: please correct the reference.

The reference has been corrected (line 316):

Using the Wille et al., (2021) AR detection algorithm based on vIVT, we are able to diagnose the local climatology of ARs making landfall over the Amundsen Sea Embayment and Marie Byrd Land.

Page 14, line 312: Add the 80degS latitude to figure 1, see comment above.

Please see response to previous comment, we have added a description of the 80 deg S boundary to Fig. 2, where it is shown through a grey mask over the interior of the Antarctic Ice Sheet.

Page 17: I miss a conclusion section to summarize the findings clearly and provide an outlook.

Section 4 combines the discussion and conclusions from the study. Based on comments from all reviewers that this section is interesting and compelling, we as co-authors have considered this option and agreed that the discussion and conclusions section is best left as it is currently formatted. By setting our conclusions in the context of broader Antarctic AR and surface mass balance research, we show how this study is part of a larger research aim to identify Antarctic ARs, diagnose their synoptic characteristics, and quantify their impacts on precipitation and surface melt. From the choice of AR detection algorithm and reanalysis products, to the AR climatology we derive, we strive to explain what critical choices were made in the data and methods, and how those may impact the results presented. Similarly with the case study, we seek to summarize how the collection of observations and reanalyses help to provide a more complete picture of the event than any single dataset alone. By combining the conclusions with the discussion, we integrate the most important findings from the study with the strengths and limitations of our methodology.

In the final two paragraphs of the section, we provide an outlook for future research on the impacts of ARs on West Antarctic surface mass balance. We discuss the dominance of snowfall over surface melting in current ARs and how more extensive rainfall and surface melting may occur in a future climate, particularly if AR intensities are amplified. We discuss the potential implications of rainfall and melting to reduce the ability of the firn layer to absorb meltwater, which may lead to the destabilization of ice shelves and accelerated mass loss. We consider that future impacts of Antarctic AR may approach the present-day impacts of Greenland ARs. Finally, we highlight the critical need to examine the representation of Antarctic ARs in climate models and how their frequency, intensity, and surface mass balance impacts may change in the future.