Climatology and Surface Impacts of Atmospheric Rivers on West Antarctica

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<u>REVIEWER COMMENT #1:</u>

Review "Climatology and Surface Impacts of Atmospheric Rivers on West Antarctica" by Michelle Maclennan and co-authors.

This manuscript investigates the climatological conditions and the surface impacts of atmospheric rivers (ARs) in West Antarctica. The author first uses reanalysis model output (MERRA-2) in combination with an AR detection tool to examine the contribution of ARs in this region from 1980 to 2020. Then for a more detailed and smaller scale perspective the authors present a case study of three successive ARs on Thwaites Glacier in February 2020, for which they use reanalysis data, in-situ measurements and a firn model. Finally, the authors discuss how ARs may change in a future climate.

The manuscript is well written with clear figures. It is an interesting and relevant study within the scope of TC. The idea and methods are not completely new, it builds on existing knowledge from ARs in Antarctica and previous firn modeling efforts. By combining large scale model output and in-situ measurements, the results are a useful contribution for understanding the climatology and impacts of atmospheric rivers in West Antarctica. Despite being a topic of interest, there are some minor aspects especially regarding the contribution/purpose, goals stated in introduction, methodology and results that might be better represented. I elaborate on this in the comments below, which follow the order of the manuscript.

> **The authors would like to thank Sanne Veldhuijsen for their feedback and for providing insightful recommendations on improving the motivation of the study and the clarity of the text. We have responded to the reviewer's comments as follows, with a particular focus on revising the last two paragraphs of the introduction and adding context to the introduction and discussion sections with references to previous studies on Antarctic ARs. 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.**

General comments/questions:

1. Contribution/purpose of this study: an elaborate introduction about AIS mass balance and atmospheric rivers is given. However, the articulation of the purpose and contribution of this study in the introduction can be improved. Articulate more clearly what is new in this study compared to previous work, the added value of this

study, what is already known about ARs this region (What have Willle et al. 2019 & 2021 found about ARs in West-Antarctica, e.g. how many per year/trend)? Also the reason why is chosen for this region (Lines 123-127) would be more suitable for this part of the introduction.

We have revised the last two paragraphs of the introduction (starting on line 58) to emphasize the motivation for our study and its contribution in the context of Antarctic ARs research. We now explain that based on previous studies, the spatial variability of extreme precipitation associated with ARs over West Antarctica is poorly understood and fails to capture the local accumulation associated with AR events. We highlight that our analysis of a case study event provides key indications of small-scale spatial variability in AR-driven accumulation and surface melting on Thwaites Eastern Ice Shelf. Finally, we now also emphasize that placing this case study within the broader context of the climatology of West Antarctic ARs enables us to better understand the characteristics and impacts of ARs on the surface mass balance.

In line 203 in the results, we now discuss how the trend in AR events we found is consistent with the trend found by Wille et al. (2021):

From 1980 to 2020, there is a positive trend in AR events of +0.12 +/- 0.06 events per year squared (p = 0.055), similar to the results from Wille et al. (2021), which also showed an increasing trend in AR frequency from 1980 to 2018 over the WAIS region.

In response to comments from another reviewer, we have revised Data and Methods section 2.2 "Reanalysis Products: MERRA-2 and ERA5" by sticking specifically to information about the reanalyses and how they are used, and removing the text on lines 123-127, which is background information already mentioned in the introduction.

2. Contrasting impacts on SMB: In Lines 76-78 you state that ARs have contrasting impacts on SMB, and that it is therefore important to study them from both large-scale climatological perspective and a case study. With contrasting impacts on SMB, I understand that you mean snowfall, melt or temperature? However, the melting (and temperature) part is not studied from the large-scale climatological perspective. Nevertheless, melt could be important on e.g. Abbot ice shelf. I think it would be good to explain in the introduction that and why the focus of the large-scale climatological perspective is on precipitation. This is probably also why you use the vIVT detection algorithm.

We have revised the last two paragraphs of the introduction to improve clarity in response to several reviewer comments, including the sentence in question here. The paragraph starting on line 58 now explains the complex impacts of ARs on the surface mass balance of the Antarctic Ice Sheet. The paragraph starting on line 70 explains the motivation for our climatology and case study and highlights the gap in prior research that our study addresses. We do not aim to quantify large-scale AR-driven surface melting in this study, which has already been studied in Wille et al. (2019), and is much smaller in magnitude than AR-driven precipitation (this is mentioned in the introduction on line 67). Here, we emphasize that analyzing the large-scale climatology of ARs themselves improves our understanding of their characteristics and surface mass balance impacts, with a focus on quantifying AR-attributed precipitation. In section 2.3, we explain the motivation for using the vIVT detection algorithm - which is indeed better suited to quantifying precipitation than the IWV detection algorithm (Wille et al., 2021).

3. Lines 85-86 "Finally, we discuss the results in the context of how ARs contribute to the present mass balance of the AIS and how their frequency and precipitation may change in future climate scenarios." I don't see where the future frequency and precipitation is discussed in the manuscript? You do discuss a potential increase in melt related to AR events. Perhaps use: "Responses and impacts of atmospheric rivers to climate change by Payne et al. (2020)", and the fact that there is an ongoing increase over time of current AR events, which might continue (Fig. 3a).

The majority of the discussion on the future of Antarctic ARs indeed focuses on increased surface melting. As mentioned above, we revised the last two paragraphs of the introduction, including the text in question. To reflect this critical component of the Discussion, we rewrote the last sentence of the introduction as follows, to focus more on how the impacts of ARs may change in the future (line 80):

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.

4. The discussion is strong and very interesting, one thing that might be added is some comparison to previous findings about ARs on the WAIS, which is mentioned above as well. (E.g. Wille et al. 2019 & 2021).

Thank you. We have added several references to the discussion section to discuss how the findings from this study compare to Scott et al. (2019), Wille et al. (2021), and Adusumilli et al. (2021).

Starting on line 325:

This pressure anomaly pattern is similar to the Pacific South-American patterns identified by Scott et al. (2019) as drivers of marine air intrusions and West Antarctic surface melting, and consistent with geopotential height anomalies identified by Adusumilli et al. (2021) during WAIS AR events in 2019. While ARs are infrequent, they cause intense precipitation in short periods of time, and account for 11% of the annual surface accumulation in this region, consistent with Wille et al. (2021).

5. Lines 373-375: "Limited by 1.5 years of in-situ data." I wonder why you only look at 1 AR family event, while there are multiple AR events each year?

   In this paper we focus on an exceptional AR family event as a case study that occurred during the unique period when automatic weather stations recorded meteorological conditions on Thwaites Eastern Ice Shelf. We perform detailed analysis of both the specific atmospheric conditions that led to the event and the surface mass balance impacts that the family event had. The motivation to use a case study event here is that it allows us to closely examine the drivers and effects of a particular event, within the broader context of the climatology of West Antarctic ARs. On average, there are 9 +/- 3 AR events on Thwaites Glacier each year. In 2020, there were 8 ARs that made landfall over Thwaites Glacier, 3 of which corresponded to the February 2020 family event. None of the remaining 5 ARs were part of family events. Furthermore, wind speed sensors on the automatic weather stations experienced riming starting in June 2020, meaning the most complete record of observations is from January - June 2020. That is why we selected the February 2020 AR family event for the case study.

Specific comments/questions:

1. Lines 63: Why is this unique for Antarctic ARs? Is this not the same for Greenland ARs?

   This is correct, Greenland ARs also have multiple effects on the SMB. Here, the comparison was aimed at highlighting how Antarctic ARs are different from midlatitude ARs. To avoid confusion, we have removed the first sentence of the paragraph and revised the following sentences to include the statement that Antarctic ARs can have multiple effects on the SMB, without calling them "unique" (line 58).

   ~~Antarctic ARs are unique in that they can have multiple, contrasting impacts on the SMB.~~ While ARs make landfall up to 14% of the time in the mid-latitudes (~50 days per year), they are comparatively rare over the AIS, making landfall only 1% of the time (or ~3 days per year, Rutz et al., 2019; Wille et al., 2021). Although they occur infrequently, Antarctic ARs can have multiple, contrasting

impacts on the SMB. ARs cause intense precipitation when they make landfall over the AIS, because they carry so much moisture.

2. Lines 66: They carry much moisture, but does the fact that the AIS is a desert not also play a role in the importance of ARs?

Yes, Antarctica is a desert, meaning that individual AR events can contribute significantly to local SMB (Gorodetskaya et al., 2014), particularly over East Antarctica. However, polar ARs are generally less moist than mid-latitude ARs, meaning the moisture threshold for Antarctic ARs is lower than the threshold in the mid-latitudes, so it is all relative (Wille et al., 2021). Additionally, Wille et al. (2021) showed that ARs contribute more of the annual SMB in East Antarctica than in West Antarctica - which experiences more total snowfall than East Antarctica (Lenaerts et al., 2019).

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

Lenaerts, J. T. M., Medley, B., Broeke, M. R., and Wouters, B. (2019): Observing and Modeling Ice Sheet Surface Mass Balance, Reviews of Geophysics, doi: 10.1029/2018RG000622

Wille, J. D., Favier, V., Gorodetskaya, I. V., Agosta, C., Kittel, C., Beeman, J. C., Jourdain, N. C., Lenaerts, J. T. M., and Codron, F. (2021): Antarctic atmospheric river climatology and precipitation impacts, Journal of Geophysical Research: Atmospheres, doi: 10.1029/2020JD033788

3. Line 72: The study of Neff et al 2014 is about Greenland.

We have moved the Neff et al. (2014) reference to the following sentence in the paragraph (line 66). We have added Wille et al. (2019, 2021) as supporting references to the following sentence as well (in response to the next comment).

This causes surface melting in coastal Antarctica, particularly on the Antarctic Peninsula, which can lead to runoff and/or deplete the ability of the firn to store future meltwater (Wille et al., 2019; ~~Neff et al., 2014~~). Unlike on the Greenland Ice Sheet (Neff et al., 2014; Mattingly et al., 2018), ARs act to increase Antarctic SMB, as they cause significantly more snowfall than surface melting (Wille et al., 2019; Wille et al., 2021).

4. Line 73: "ARs act to increase Antarctic SMB, as they cause significantly more snowfall than surface melting". Can you give a reference for this statement?

Yes, we have added Wille et al., (2019, 2021) to support the statement, please see previous comment.

5. Lines 81-82: “to provide key insights on in-situ conditions” this can be rephrased. In-situ is often only used to describe the way a measurement is taken, maybe replace by local conditions.

We have rewritten this section in response to Reviewer Comment #4, and the phrase in question has been revised as follows (line 77):

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.

6. Line 93: basal channel?

Yes, a basal channel - we have added this in (line 89):

Cavity Camp is located on a flat part of Thwaites Eastern Ice Shelf, whereas Channel Camp sits within the surface expression of a basal melt channel (Alley et al., 2016).

Alley, K.E., Scambos, T.A., Siegfried, M.R. and Fricker, H.A. (2016). Impacts of warm water on Antarctic ice shelf stability through basal channel formation. Nature Geoscience, doi: 10.1038/ngeo2675

7. Section 2.2: Is there a reason why you chose MERRA-2 instead of ERA-5? Perhaps you can add that both reanalysis products give similar results in Wille et al. 2021.

We have added a sentence to section 2.2 describing why we choose to use MERRA-2 (line 114):

We primarily use MERRA-2 analyze the large-scale synoptics and impacts of AR events in West Antarctica, as MERRA-2 explicitly represents ice sheet hydrological and energy budgets and compares best to ice core records of snow accumulation in Antarctica among multiple reanalyses (Gelaro et al., 2017; Medley and Thomas, 2019).

8. Line 135: Not over the AIS but over the WAIS.

We have changed "AIS" to "WAIS" (line 133):

We use a polar-specific AR detection algorithm produced by Wille et al. (2021) to identify the occurrence and landfall of ARs over the WAIS.

9. Line 153: Actually, you use three different approaches, also the GNSS measurements.

We have eliminated this sentence, and the following sentence, to omit the discussion of reanalysis products in section 2.4 and focus on the SNOWPACK modeling (line 151). Thereby we have also deleted our mention of the number of approaches.

~~***We determine the accumulation attributed to the case study AR event of February 2020 using two distinct approaches. In the first, we use precipitation from MERRA-2 and ERA5 reanalyses. In the second,***~~ ***We use observed snow height from the AMIGOS to force the firn model SNOWPACK to reconstruct accumulation during the AR case study event in February 2020.***

10. Section 2.4: I think it can be clarified how the firn modelling works. Perhaps add that snowfall is assumed to occur when measured snow height exceeds the modeled snow height. Strictly speaking, there can also be snowfall when the observed snow height remains stable e.g. if there is snowfall in combination with densification, sublimation or melt. The difference between the observed and modelled snow height is then added to the snowpack, which can be converted with the fresh snow density to accumulation.

    The reviewer indeed provides a clearer description of our use of the SNOWPACK model. We improved our description in the manuscript (section 2.4, starting on line 151):

    We use observed snow height and temperature from the AMIGOS to force the firn model SNOWPACK (Lehning et al., 2002a, b) to reconstruct accumulation and surface melt during the AR case study event in February 2020. SNOWPACK is a physics-based, multi-layer firn model (Lehning et al., 2002a, b) which has been extensively applied in polar regions (Groot Zwaaftink et al., 2013; Steger et al., 2017; Van Wessem et al., 2021; Keenan et al., 2021). The model calculates snow compaction using an overburden formulation and solves the full surface energy balance to provide the upper boundary condition for solving the temperature equation and calculating melt. When snow accumulates, fresh accumulation density is calculated as a function of meteorological conditions, particularly wind and the presence of drifting snow (Keenan et al., 2021; Wever et al., 2022). We configure the SNOWPACK model here to derive snowfall from the observed snow height: if observed snow height exceeds the simulated snow height, the difference is interpreted as snowfall, when relative humidity, air temperature and snow surface temperature meet snowfall conditions (Lehning et al., 1999; Wever et al., 2015). This is then combined with fresh accumulation density, to convert to accumulated mass.

11. Line 190-191: Perhaps start the results section with one sentence describing the kind of results you are going to show in Figure 2, as an introduction to the reader. Also refer to panels of figures if that is the case, so Figure 2a e.g in Line 193.

    We have added a sentence to the beginning of the paragraph to introduce AR frequency and how it is calculated. We moved the reference to Fig. 2 in the first sentence of the results to the third sentence, where we discuss local AR frequencies. We have added references to specific panels of Fig. 2 (a, b, and c) in the revised text below (line 195):

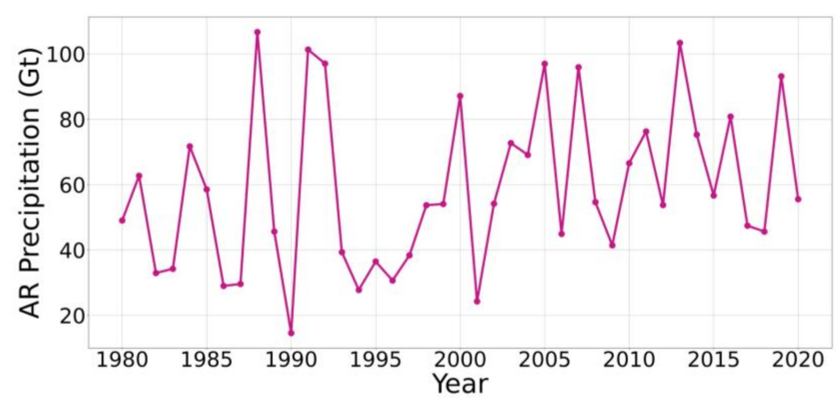
To determine the frequency of ARs over the Amundsen Sea Embayment and Marie Byrd Land region, we divide the number of AR times by the total time from 1980 to 2020. Our analyses show that ARs exhibit a total frequency of 3.2% over the whole region from 1980 to 2020 (i.e., there is an AR making landfall somewhere in the region 3.2% of the time, on average) (~~Fig. 2~~). ~~This represents the total frequency of ARs over the region, calculated by dividing the number of AR times by the total time from 1980 to 2020.~~ Within the region, localized AR frequencies range from 0.2 to 0.8% of the time, with the highest frequencies over the Abbot Ice Shelf and the Getz Ice Shelf (Fig. 2a). Integrated over the entire region, ARs contribute 59 +/- (one standard deviation) 24 Gt precipitation annually (out of 550 +/- 63 Gt total annual precipitation, Fig. 2b and c), and explain 28.7% of the interannual variability in precipitation (linear trends removed).

12. Lines 190-191: the 3.2% in combination with the reference to figure 2 is a bit confusing as I don't see 3.2% in the figure. Also I suggest to first give the definition of frequency of ARs and then discuss the numbers.

    Please see response to previous comment - we have added an introductory sentence with a definition of AR frequency, and moved the reference to Fig. 2a to a later sentence which discusses local AR frequencies over the region.

13. Figure 3: Would it not also be interesting (and possible) to have a third graph with the amount of precipitation from ARs over time?

    We have shown the annual mean contribution of ARs to precipitation over the Amundsen Sea Embayment and Marie Byrd Land spatially in Fig. 2b and c, and we describe the integrated annual mean precipitation in the first paragraph of the results. However, we agree that the time series of AR precipitation complements the time series of AR events in Fig. 3a. Therefore, we have added a Fig. 3c, which is a time series of AR-attributed precipitation by year from 1980-2015:



14. Caption Figure 5: I suggest to add that this figure is about Thwaites Eastern Ice Shelf.

We have added "Thwaites Eastern Ice Shelf" to the first sentence of the Fig. 5 caption.

MERRA-2 2 m temperature difference by season between the average temperature 24 hours before AR landfall and the average temperature 24 hours starting at AR landfall (post- minus pre-event) from MERRA-2 reanalysis over Thwaites Eastern Ice Shelf.

15. Line 228: The temperature decrease is not only in the winter right?

    We assume that the comment is referring to this statement (line 231):

    Here we see the largest increases in temperature associated with the landfall of winter AR events.

    On average, we observe a temperature increase in all seasons; however, the largest temperature increases occur in the winter season.

16. Line 228: perhaps omit: "from the mean 24 hrs before landfall to the mean 24 hrs after landfall." as this should already be clear.

    We assume that this comment refers to line 225:

    To do this, we take the difference between the mean MERRA-2 2 m temperature 24 hrs before landfall, and the mean 2 m temperature 24 hrs after landfall.

    We will keep this sentence in the results because it is explicit about the method used to calculate the change in temperature during AR events, and we (the co-authors) are in agreement that this phrase is important for the clarity of the results.

17. Caption Figure 6: Line 1 omit repetition of "on TG".

    Thank you for pointing this out, we have removed the repetition of "on TG" from the first sentence of the Fig. 6 caption:

    3 ARs make landfall on TG in short succession ~~on TG~~ on (a, d) February 2, (b, e) February 4, and (c, f) February 7, 2020.

18. Line 281: Should "different spatial resolution" not be "low spatial resolution"?

    We have changed the wording to "lower spatial resolution" (line 288).

    While the snow height observations at Cavity Camp and Channel Camp and represent point locations, the accumulation in the reanalyses represents a grid-cell average. Therefore, the reanalyses may partly underestimate local accumulation on Thwaites Eastern Ice Shelf, particularly during extreme events, due to the lower spatial resolution.

19. Line 281: Perhaps include in method section 2.4 that you calculate surface melt from the SNOWPACK model.

We added that the SNOWPACK model calculates the full surface energy balance to provide the upper boundary condition for the temperature equation and to calculate melt (line 154):

The model calculates snow compaction using an overburden formulation and solves the full surface energy balance to provide the upper boundary condition for solving the temperature equation and calculating melt.

20. Caption Figure 8: Line 2: atmospheric conditions are used "to" force SNOWPACK.

We have added "to" to the sentence in the Fig. 8 caption:

AMIGOS observations of snow height and atmospheric conditions are used to force SNOWPACK with radiation provided by MERRA-2.

21. Line 306: Improve the reference formatting.

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.

22. Line 320: From Wille et al. 2021 I understand that 10% of total snowfall comes from AR events. The percentage of extreme precipitation events explained by ARs depend on the threshold but is 10% lower in West Antarctica than East Antarctica (where it is 25-45%).

Wille et al. (2021) states that in West Antarctica, approximately 10% of the total annual snowfall comes from AR events. In East Antarctica, 10-20% of the total annual snowfall comes from AR events. The percentage of extreme precipitation events explained by ARs at the 90th percentile is 25-35% in East Antarctica. Fig. 4a in Wille et al. (2021) shows that over West Antarctica, the percentage of extreme precipitation events explained by ARs at the 90th percentile is 10%. Wille et al. (2021) states that on average, ARs explain 10% more extreme precipitation events in East Antarctica than in West Antarctica.

23. Line 356-357: "As surface-based temperature inversions are least developed in austral summer, the baseline surface temperatures before AR events are nearest the melting point in summer." And also because it is simply warmer in summer?

Yes - we have added this in to the sentence (line 369):

As surface-based temperature inversions are least developed in austral summer, and air temperature is higher than in other seasons, the baseline surface temperatures before AR events are nearest the melting point in summer.