Response to the comments from reviewer 1

Summary

In this paper, Zhang and coauthors present a modified Atmospheric River Scale tailored to analyze AR events in the polar regions. They first describe the justification for a polar AR scale by comparing the integrated water vapor transport (IVT) climatology in polar regions to the mid-latitudes, finding that most ARs impacting Greenland and Antarctica would go undetected by the original AR scale due to the colder and drier conditions in the polar regions. They introduce a modified version of the AR scale that includes three new "polar" categories with lower IVT thresholds, then use this scale to analyze the frequency, seasonality, and interannual trends in polar ARs. They assess the precipitation and melt impacts of the ARs identified by the new scale, finding that weak and moderate ARs account for most AR-related precipitation in Greenland and Antarctica, while stronger ARs are infrequent but cause extreme precipitation when they occur. Finally, they describe a web product that provides polar AR forecasts in real time.

The paper is well-organized and well-written overall. Most figures are clear and the references are extensive and appropriate. In my assessment the polar AR scale will be highly useful to a broad range of users, and I am impressed by how much information about ARs in Greenland and Antarctica can be captured by this simple but well-designed scale. However, I think there may be a serious error in the ice sheet melt analysis that should be addressed before the paper can be published, as described in my major comment below. I also have a number of minor comments and technical corrections, as described below.

We appreciate the valuable comments from reviewer 1.

Our responses are in blue below each comment from the reviewer.

Major comments

(1) I strongly suspect there is some error in the analysis of surface melt in Fig. 13. Numerous studies have documented an increase in Greenland Ice Sheet melt during the 21st century, but Fig. 13b shows more summer days with surface melt even in the 1980s compared with the 2000s. This is almost certainly incorrect. For a quick check, compare the years 1993 and 2012 using the Greenland Surface Melt Extent Interactive Chart at the National Snow and Ice Data Center Ice Sheets Today page (https://nsidc.org/ice-sheets-today/melt-data-tools). The NSIDC chart shows a much more extensive Greenland melt area throughout virtually all of JJA in 2012 compared to 1993, but Fig. 11b taken literally shows that 1993 was the most extensive melt year along the Greenland coast and had over 3 times the melt days of 2012. This figure also doesn't line up with Fig. 11b which shows increasing AR frequency along the Greenland coastline.

I am less familiar with melt trends in Antarctica so I am not sure if Figs. 13a and 13c contain obvious errors. The authors should check their analysis and the underlying microwave melt dataset in both Greenland and Antarctica for potential errors in processing.

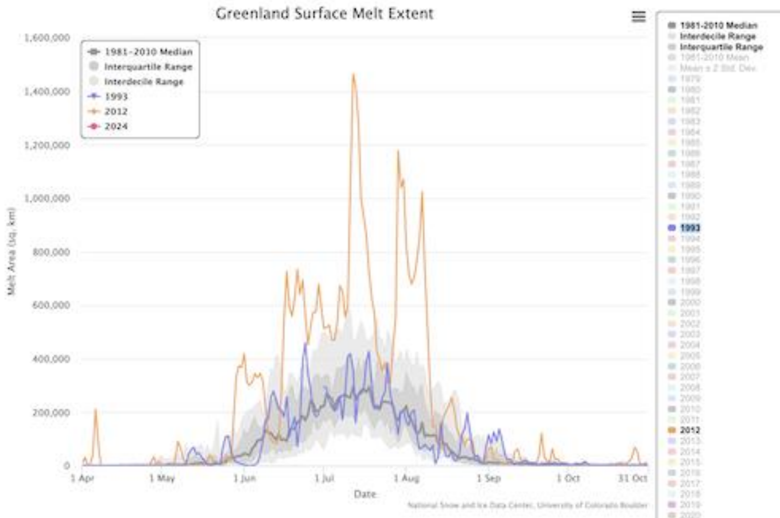

figure shared by reviewer

We checked the calculation of surface melt in Fig.13 and found an issue caused by the missing data along the coastline of Greenland. Specifically, we used the grids along the coastline of Greenland (as shown in Fig.4c) for the analysis of Figs.13b&d, but the surface melt dataset has missing data in about one third of those grid cells on average during 1980-2022. Then we excluded the missing data, but the surface melt along the Greenland coastline still did not show a significant increase trend through the 21st century. The melt data from the limited number of coastal grid cells might introduce some uncertainties, and the result might be misleading.

Therefore, we re-calculated the surface melt for the entire Greenland using all grids with valid data instead of the coastline and re-created Figs.13b&d. In the new results, the surface melt in Greenland has a significant increase trend (+0.89 days per decade, P value = 0.002, the trend line was added in Fig.13b). The melt days in 2012 JJA is nearly doubled compared to the melt days in 1993 JJA. These are consistent with previous studies and the chart from NSIDC that the reviewer shared.

The Antarctica coastline has a similar missing data issue, although the impact seems not as large as for the Greenland coastline. To ensure reliability and keep consistency in Fig.13, we re-created Figs.13a&c to show the surface melt for Antarctica instead of the Antarctic coastline. In Antarctica, the surface melt data does not include the area higher than 1700 m of altitude, where melting is unlikely. The surface melt in Antarctica has a slight but not statistically significant decrease trend (-0.10 days per decade, P value = 0.135). This result is consistent with previous studies, which showed that there are no significant changes or slight decrease trend in surface melt in Antarctica.

The new Fig.13 shows that 23% and 26% of the surface melt is associated with ARs in Antarctica and Greenland respectively. We revised the text accordingly in Section 4.2 Surface melt and polar ARs (see tracked changes in the manuscript).

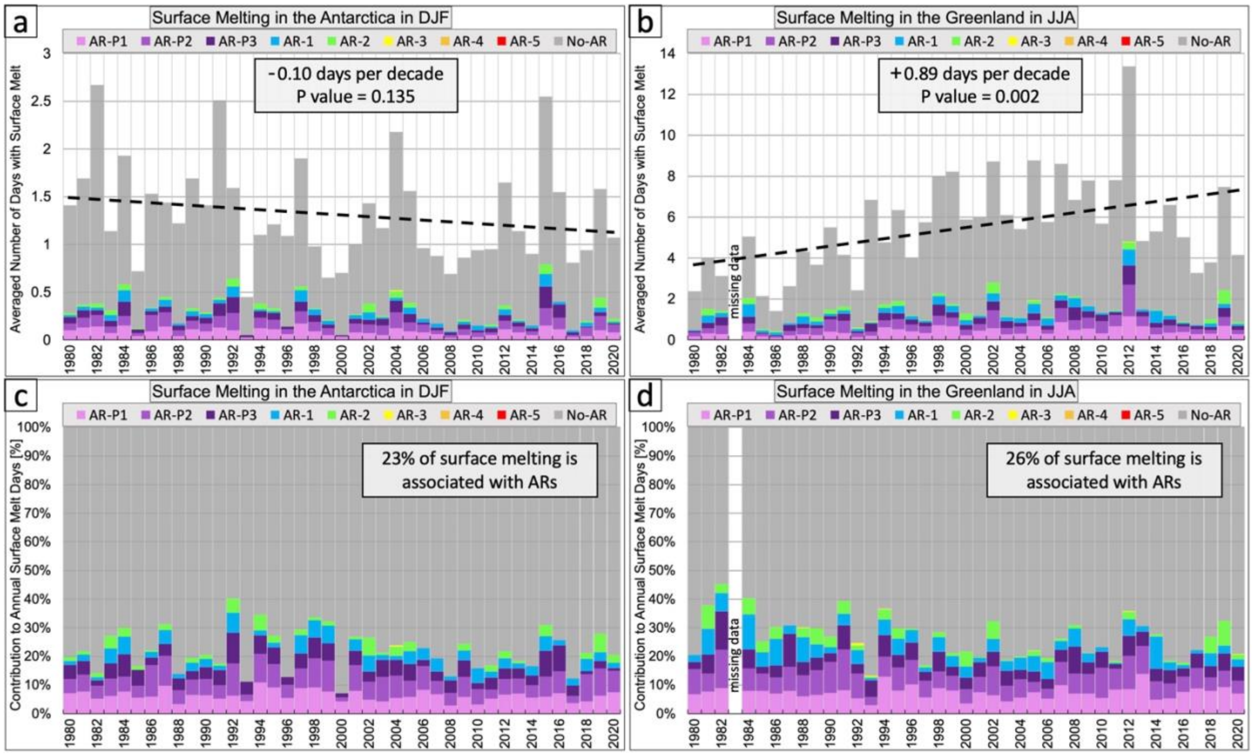

Figure: The new Fig.13 in the manuscript. The surface melt was calculated in the entire Antarctica and Greenland instead of the coastlines.

Minor comments

(1) General comment: Have the authors thought about adjustments to the polar AR scale that may need needed in future warming scenarios? Will the AR scale remain constant in climate change scenarios, despite the projected increases in IVT in the polar regions? Any new analysis on this topic is likely outside the scope of this manuscript, but it could be a nice addition to the paper to discuss this as a topic for future research in the conclusions section.

We agree that the future change of polar ARs is an important research topic, which is closely related to the future changes in the extreme weather trigged by ARs and the relevant surface mass balance in Antarctica and Greenland, but it is out of the scope of this manuscript as the reviewer mentioned. Following the reviewer’s suggestion, we included some relevant discussion in Section 6. Conclusions and discussion (see tracked changes). Generally, both relative and fixed IVT thresholds were used to quantify the future changes of ARs in previous studies depending on different study goals. The AR scale is designed to objectively quantify the impact and strength of ARs based on their intensity and duration. Therefore, it is ideal to keep the IVT thresholds of the AR scale consistent under climate change. Because ARs with stronger IVT usually have higher impacts (e.g., more precipitation), and it is reasonable to rank them as a higher AR scale using consistent IVT thresholds in polar AR scale.

(2) Title: I suggest removing "CW3E" from the title, or at least stating the full name of the Center for Western Weather and Water Extremes in the title. The abbreviation "CW3E" will not be familiar to many in the cryospheric science readership of this journal. I also note that the Polar AR Scale is described as a collaborative effort between CW3E and the Byrd Center at Ohio State (L523–526), and the paper introducing the original scale (Ralph et al., 2019) does not describe it as the "CW3E Atmospheric River Scale".

We spelled out "CW3E" in the title, so the new title is "Extending the Center for Western Weather and Water Extremes (CW3E) Atmospheric River Scale to the Polar Regions". Both the regular AR scale introduced by Ralph et al. 2019 and the extended polar AR scale in this manuscript are led by CW3E. Therefore, we included CW3E in the title.

(3) L44: I suggest framing this sentence along the lines of "Our results show that that the polar AR scale better characterizes the strength and impacts of ARs in the Antarctic and Arctic regions than the original AR scale, and has the potential..."

We revised that sentence as suggested.

(4) L170–171: Why were 1-degree ERA5 data used instead of the finer native resolution of ERA5? Do the authors expect that this has any influence on their results? I note that the original AR Scale in Ralph et al. (2019) used 0.5-degree gridded data.

We use 1-degree ERA5 data in this manuscript since we are examining the AR scale in polar regions. The zonal length of a 1-degree grid cell in polar regions (e.g., ~38km at 70N/S) is roughly close to the zonal length of a 0.5-degree grid cell at middle latitudes (e.g., ~39km at 45N/S). Meanwhile, ARs are relatively large objects, which are usually a few hundreds to a couple of thousands of kilometers in size. Therefore, we think the 1-degree resolution is sufficient to examine the features of polar ARs. Another reason is that we planned to include a section to explore the uncertainties in the AR scale due to different reanalysis datasets and we used the 1-degree common grid. However, we did not include that part in the manuscript eventually due to the difference in IVT calculation. The IVT from ERA5 was calculated using model levels from the surface to the top of the atmosphere while the other reanalysis datasets only provide Q, U, and V at pressure levels. The uncertainties in the AR scale based on different reanalysis datasets might be caused by the different IVT calculation methods rather than the data itself. Therefore, we did not include that part in this manuscript.

A finer resolution (e.g., 0.25-degree) might capture a higher maximum IVT value in some extreme AR cases compared to the 1-degree resolution. However, given the large interval between IVT thresholds (50 kg/m/s for AR P1 – AR P3 and 250 kg/m/s for AR1 and higher ranks), using a finer resolution does not have a significant impact on the climatological results in this manuscript. Beyond this manuscript, different resolutions could be used accordingly in the polar AR scale framework for different research or applications (climate or weather, large-scale or local scale, etc.).

(5) L218–228: This is a nice analysis of the climatology of IVT in the parts of Greenland and Antarctica that extend outside of the polar latitudes.

Yes, it has a small impact on some of the results (e.g., Fig.4 and Fig.9) if we include the southern part of Greenland that extends outside of the polar latitudes. However, that narrow part extends to 60°N and is surrounded by a relatively warm ocean, which has a different climatology from the part within the polar region. Thus, we did not include that part in the main body of the manuscript. On the other hand, that the southern part is an important part of Greenland, so we repeated the analysis to include that part and showed the results in the Supplement. The impact from the small tip of the Antarctic Peninsula is ignorable, so we did not include the corresponding figures.

(6) L286–287, 319–321: Out of curiosity, do the authors know how many AR4 events there are in the historical record in Antarctica? I see in L456–457 that no AR5 events have ever been recorded in Antarctica, but it would be nice to state the number of AR4 events here to provide historical context for the March 2022 event. Would it be straightforward for the authors to include a map of the maximum AR category ever reached in the historical record at the Antarctic coastline points shown in Fig. 6d?

There was only one AR4 event identified during 1979-2022 in Antarctica, the extreme AR in March 2022 as shown in Fig.1 and Fig.6 (Fig.S3 in the revised version). It covered eight locations/grids along the coastline of the East Antarctica. We add a couple of sentences in Section 3.1 to clarify that.

This manuscript focuses on introducing the extended AR scale for polar regions and providing the relevant statistical results from a climatology perspective, which are usually less sensitive to the input data (e.g., the spatial and temporal resolution of the IVT data). However, the maximum AR scale in the historical record at a specific location has large uncertainties due to many factors, like the spatial and temporal resolution of the IVT data (e.g., 1.0 degree vs. 0.25 degree, 6-hourly vs. hourly), the calculation of IVT (integrated at model levels or limited number of pressure levels), or the different datasets (different reanalysis datasets or observation). Therefore, we did not include a figure showing the maximum AR scale events in the historical record at specific locations, which might include large uncertainties and be misleading.

We agree that a study focusing on the most extreme landfalling AR events along different locations of the Antarctic coast during the historical record is a good follow-up research.

(7) Figure 6d and elsewhere: How / why were the locations of the these points along the Antarctic coastline chosen to calculate AR scale data? Are they selected to be useful for particular communities, such as Antarctic research stations?

Basically, the dots in Fig.6d are located every 5 degrees in longitude along most parts of the Antarctic coastline. Meanwhile, there are additional locations along the coastline of the Antarctic Peninsula since it has a complex topography and coastline, and it is an area with more AR activities. In addition, we also included a dot at the Dome C station in the East Antarctic since it is an important observation site.

In this manuscript, we focus on the coastal regions of Antarctica and Greenland. The CW3E AR Scale Forecast tools for Antarctica described in Section 5 will include more locations according to research interests and application needs.

(8) Fig. 7: To help interpret these maps, it would help to add a few solid contours with contour labels. Perhaps the contours of 1, 5, and 10 average annual ARs could be labeled.

We used a different color map for both Fig.7 and Fig.8 so it is easier to read the AR frequency.

(9) Fig. 8: Why are there more AR 2 events (panel e) in this "Atlantic Arctic gateway" region than ARs in the weaker AR P1 through AR 1 categories (panels a–d)? Is this correct?

We checked the results in Fig.8 with a focus on the Atlantic Arctic gateway region and the results are correct. The Atlantic Arctic gateway region is quite different from the other regions along the north polar circle. It is the only wide and open ocean area along the north polar circle, and the extratropical cyclones (usually acting as a dynamical driver of ARs) are very active and relatively stronger over that region along the Atlantic storm track. As a result, the ARs over that region usually have a stronger IVT and a longer duration. Therefore, the ARs there tend to have relatively higher ranks with a maximum frequency in AR2.

(10) L385–389: Nice analysis of the seasonality of Greenland ARs. This is an interesting result and Fig. 10 is an interesting figure.

In addition to the current description and interpretation about the seasonality of ARs, we rewrote some of the discussion in the manuscript about the reasons for this seasonality (see the tracked changes in the manuscript).

(11) L445–456: How / why was this 12-hour window chosen to define AR-associated precipitation? Is there precedent for this method in the literature? I have not performed an extensive literature review but I note that Maclennan et al. (2022) defined AR-associated precipitation in Antarctica using precipitation from the time of the AR + the following 24 hours.

For a specific location, we considered precipitation under AR conditions, 12 hours before, and 12 hours after AR as the precipitation associated with ARs. This time window (from 12 hours before to 12 hours after AR) was selected because we found that precipitation occurs not only under AR conditions but also about 12 hours before and after AR, although the variability of the time window is large. Meanwhile, some previous studies (e.g., Maclennan et al., 2022 and Wille et al., 2021) defined the precipitation under AR conditions and within 24 hours after AR as the precipitation associated with ARs.

To better define the precipitation associated with ARs, we re-calculated the precipitation occurrence before and after AR conditions for the Antarctic and Greenland coasts. The results show that on average the precipitation rate after AR conditions decreases with time and the precipitation rate during the first 12 hours (0-12 hours after AR) is higher than the second 12 hours (12-24 hours after AR). This is consistent with Fig.1 from Maclennan et al., 2022. Meanwhile, we found that the precipitation rate in the 12 hours before AR is comparable to the second 12 hours (12-24 hours) after AR, but with a larger variability indicating the precipitation difference from case to case is larger in the 12 hours before AR.

Therefore, in the revised manuscript we decided to follow the previous studies (Maclennan et al., 2022; Wille et al., 2021) to define the precipitation under AR conditions and within 24 hours after AR conditions as the precipitation associated with ARs. The updated Fig.12 has very small differences from the old version (12 hours before and after AR). For example, the contributions of all ARs to the total precipitation are 32.0% and 32.2% for the Antarctic and Greenland coast, which are slightly different from the previous 32.4% and 31.8%. This is not surprising since most AR-related precipitation occurs under AR conditions and within 12 hours after that. We also revised the description and discussion in the manuscript accordingly.

(12) L484–485: This delay of 18–24 hours found by Mattingly et al. (2023) applies specifically to the delay between AR landfall in northwest Greenland and melt in northeast Greenland due to the foehn effect, not generally to all Greenland ARs.

Mattingly et al. (2023) found that there is a delay of 18–24 h between AR landfall in northwest Greenland and maximum foehn-induced melt in northeast Greenland, but the melt associated with ARs occurs during the period of -48 to +48 hours (mainly -24 to +48 hours) surrounding ARs as shown in their Fig.5c (copied below). In addition, Wille et al. (2019) found that after an AR makes landfall, the residual high precipitable water and resulting mixed-phase clouds continue to cause surface melt for around five days until the airmass is transported away in Antarctica. Therefore, if the melt occurs on the identified AR days or within one day before or two days after the AR days, the melt is classified as AR-related melt. We revised the relevant sentences to clarify that.

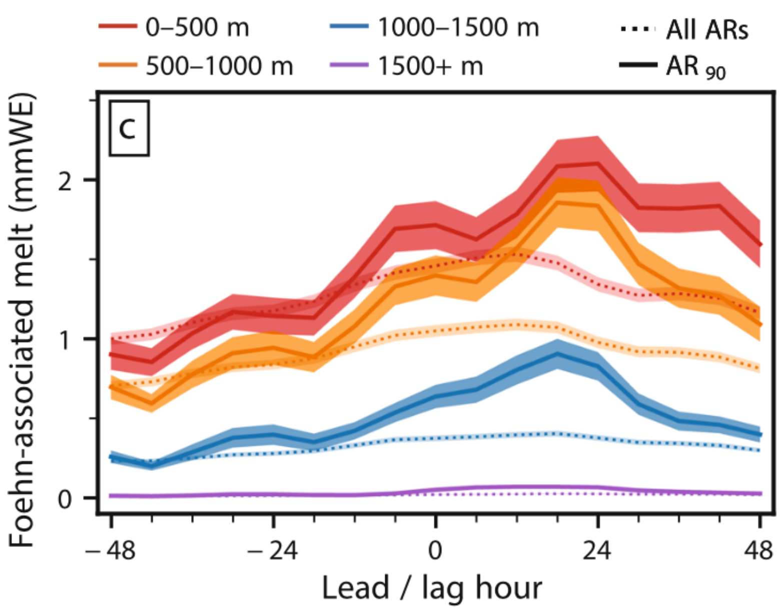

Figure: Fig.5c from Mattingly et al. (2023), temporal evolution of foehn-driven melt in northeast Greenland in 500 m elevation bands during the −48 to +48 h period surrounding northwest Greenland ARs.

(13) L546–548: Are there any plans to extend the CW3E polar AR scale forecasts to the Arctic, and to Greenland in particular? I could envision it being highly useful to the scientific and public communities in Greenland.

The CW3E polar AR scale forecast products for Greenland are in preparation. Similar to the Antarctic AR scale forecasts, we aim to provide AR Scale forecasts for Greenland based on dynamical model forecast data and the polar AR scale introduced in this manuscript. We added a couple of sentences at the end of Section 5 to mention that.

Technical corrections

- L35: application --> applications

Revised as suggested.

- L36: "the intensity"... of what? IVT?

It is the intensity of IVT. We revised that sentence to clarify.

- L38 and elsewhere (e.g. L568): Find a better word than "insufficient" to describe the unsuitability of the standard AR scale. I suggest "unsuitable". "Insufficient" implies that the scale does not reach high enough IVT values to characterize polar ARs, but the opposite is actually the case.

Here, we use "insufficient" to indicate that the ranks of the regular AR scale are not sufficient to cover the low-IVT polar ARs, so we need the extended ranks for polar ARs. We did not use "unsuitable" because the regular AR scale (AR1 – AR5) can still be used for polar ARs, and "unsuitable" may be misleading.

- L43: Antarctic --> Antarctica

Revised as suggested.

- L46: "observation, research, and forecasts" – this list is a grammatically incorrect mixture of singular and plural verbs. Please revise.

We revised it to "… to enhance communications across observation, research, and forecast for polar regions".

- L71: "the diabatic process" --> "diabatic heating"?

Revised as suggested.

- L75: "the polar ice" --> "the polar cryosphere"

Revised as suggested.

- L116: starts --> start

Revised as suggested.

- Fig. 1 caption: Labels b and c don't match the figure panels. They refer to panels c and b in the figure.

We corrected the caption of Fig.1 to match the labels b and c.

- L158: its --> their

Revised as suggested.

- L158, 525: The abbreviation "CW3E" is defined in multiple places in the manuscript.

We kept the full name of CW3E at the first place and removed the others.

- L170 and elsewhere (e.g. L177, L180): "data was" --> "data were". (The word "data" is a plural noun. Please check this throughout the manuscript.)

We revised it as suggested and also checked throughout the manuscript.

- L174: The abbreviation "EA" is not defined anywhere in the manuscript.

We changed “EA” to “East Antarctica”.

- L191, L196: The phrases "southern hemisphere" and "northern hemisphere" are not capitalized in this paragraph, but "Southern Hemisphere" and "Northern Hemisphere" are capitalized elsewhere in the manuscript (e.g. L204–205, L397). Please be consist with capitalization.

We used "Southern Hemisphere" and "Northern Hemisphere" through the manuscript.

- L199: A space is needed before the opening parenthesis in "(Fig. 3b)".

We added the space there.

- L204: The caption states that the maps show the Southern and Northern Hemisphere, but technically the maps only show the mid- and high-latitude areas of each hemisphere.

We changed it to “… the middle and high latitudes of the Southern Hemisphere (a) and Northern Hemisphere (b) …” in the caption.

- L212: percentages --> percentiles

Revised as suggested.

- L253: What are "variant" meteorological conditions? Please rephrase.

We rephrased that to "… associated with different meteorological conditions, such as the precipitation amount and rate."

- L330: Rather than "the gap between Greenland and Northern Europe", a more specific term that is often used to describe this region in the atmospheric and marine science literature is the "Atlantic gateway to the Arctic", or it could also be described as the "Nordic Seas".

We used "Atlantic gateway to the Arctic" instead of "the gap between Greenland and Northern Europe" as suggested.

- L426: increase --> increasing

Revised as suggested.

- L555: An open parenthesis is missing before the word "colored"

We added the open parenthesis.

- L603: was --> were

Revised as suggested.

- L608: illustrating --> illustrative

Revised as suggested.