Dear reviewers,

Based on your thorough and helpful feedback, we are pleased to submit a revised version of our manuscript ‘Impact, drivers and pathways of two Arctic atmospheric rivers in April 2020’.

To address the comments, we have implemented the following main changes:

- Throughout the manuscript, we refer to the first AR reaching the Arctic as ‘*Eurasian AR*’ and to its route as ‘*Eurasian pathway*’.
- We have added a panel to Fig. 5 showing the absolute precipitation accumulated over the target period.
- We have modified Figs. 7 and 10 to show the density of trajectory points per km^2 to account for varying bin sizes at different latitudes. Figs. 9 and 12 also take the grid size into account and show the moisture uptake and loss per km^2.

Below, you can find our detailed point-by-point responses to all comments in blue. Small changes that incurred since we uploaded our first responses are indicated in purple. The reviewer comments can be found on:

Reviewer 1: page 2

Reviewer 2: page 6

Reviewer 3: page 15

Reviewer 4: page 21

Reviewer 5: page 24

We believe our manuscript has greatly benefitted from the reviewers’ comments. We hope that the revised manuscript meets the standards of the journal and thank the reviewers and the editor for their time and effort.

Kind regards,
Luisa E. Avilés-Podgurski, on behalf of all co-authors

Reply on RC1

Major Comments:

Q: Lines 99 – 100: The abstract does a wonderful job detailing why the low- and high-pressure systems associated with the Arctic ARs were considered to be unusual. However, the features that define them as unusual are not defined in the main body of the text. It may be useful to include a description of what makes these pressure systems unusual at or before this point. A more complete definition is provided between lines 190 – 195, but it would benefit the reader to include a broader definition earlier in the paper.
A: We thank the reviewer for this helpful suggestion. We agree that the term 'unusual' in reference to the driving cyclones and anticyclones requires a clearer explanation earlier in the manuscript. We have therefore expanded the description in the methods section 2.1. The revised text now reads: '*For MSLP, we examine the persistent intensity of low- and high-pressure systems associated with the Arctic ARs at their respective locations. For this, we determine the 7-day mean MSLP anomaly field for the target period and define bounding boxes enclosing each weather system. For each box, we construct a reference distribution of 7-day mean MSLP anomalies for April 1979–2023. The percentile of the target period anomaly is then computed within this distribution.*'
See lines 118-121 on page 4.

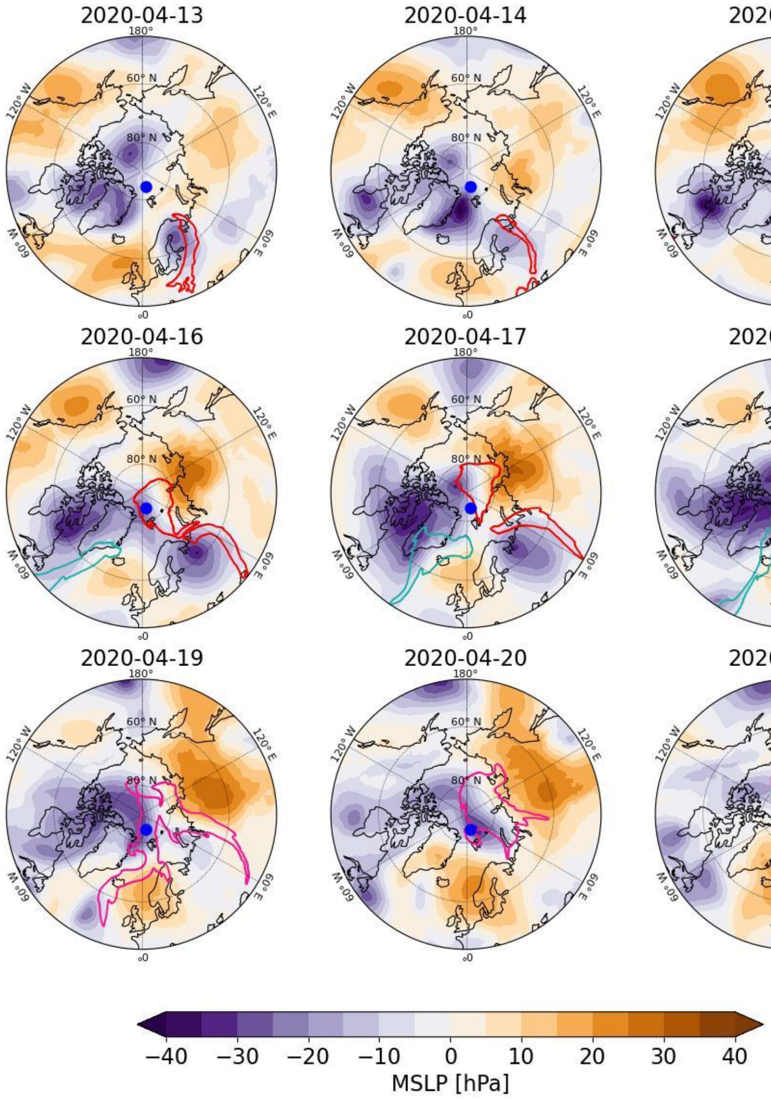
Q: Line 146: In the AR detection section, tARget v4 has Eulerian and Lagrangian tracking capabilities. In the Lagrangian parcel tracking section, it might be helpful to clarify why LAGRANTO v2.0 is being used and why the Lagrangian tracking features of tARget v4 aren't capable of achieving the goals that LAGRANTO v2.0 is being used for.
A: We thank the reviewer for raising this point. We now clarify the distinction between the two tools in the revised manuscript. While tARget v4 includes Lagrangian tracking capabilities, these are designed to track AR objects through space and time to record key life cycle characteristics such as lifetime and travel distance (Guan and Waliser, 2024). For the purposes of this study, we require full three-dimensional kinematic back-trajectory calculations to track individual air parcel pathways with flexible control over trajectory length, temporal resolution, and vertical motion constraints. LAGRANTO v2.0 is specifically designed for this type of detailed meteorological trajectory analysis (Sprenger and Wernli, 2015).

We have added a sentence in in Section 2.5 to clarify this rationale: '*While tARget v4 (see Sect. 2.4) includes Lagrangian feature tracking, it is limited to tracking the displacement of ARs over time, i.e. the propagation of a coherent pattern, which may* *move at a different speed and direction than the underlying airflow. LAGRANTO v2.0, by contrast, conducts air parcel tracking, computing full 3-D kinematic trajectories of individual air parcels that are essential for assessing sources and sinks of heat and moisture.'* This clarification now appears in lines 167-171 on page 6.

Minor Comments:

Q: Figure 1: It is slightly hard to tell which AR is of Atlantic or Siberian origin. Perhaps different contour colors can be used, with one color denoting the Atlantic AR and another color denoting the Siberian AR.

A: Different contour colours now indicate the Eurasian, Atlantic and merged AR outlines (see below). The figure caption now reads: '*Red (teal) contours outline the shapes of the Eurasian (Atlantic) AR at 12:00 UTC of the respective days diagnosed from the tARget database. After the ARs merge, the contours are shown in pink.*'



Q: Figure 3: The y-axis label on subplot (d) is a bit awkward to read. Is it possible to add more white space between the two columns of plots (e.g., between the subplots (a) and (c) column and the subplots (b) and (d) column)?
A: Fixed.

Q: Lines 29 – 31: It is mentioned that ARs enter the Arctic via the Pacific and North Atlantic sectors. Following that, it is mentioned that this is due to cyclones forming and deepening near Greenland. In this case, are Greenland cyclones responsible for both Pacific and North Atlantic AR intrusion? Further clarification might be needed for the mechanism that drives Pacific AR intrusion.
A: Thank you for pointing out this ambiguity. We have now clarified the text to distinguish more clearly between the mechanisms responsible for ARs entering the Arctic from the Pacific and Atlantic sectors. The revised passage now reads: '*Key regions include the Pacific sector and, in the Atlantic sector, the Nordic, Barents, and Kara Seas (Gong et al., 2025; Nash et al., 2018; Woods et al., 2013). Previous studies have emphasised the role of cyclone–anticyclone couplets in steering ARs into the Arctic (Gong et al., 2024). In the Atlantic sector, ARs are typically linked to cyclones that develop and deepen near Greenland, coupled with anticyclones over Scandinavia and Siberia (Papritz et al., 2022; Woods et al., 2013).*' See lines 29-32 on page 2.

Q: Line 93: It is mentioned that precipitation and rainfall data are retrieved from ERA5. Are these variables the same, or is the precipitation variable measuring both rainfall and snowfall?
A: We thank the reviewer for raising this point. Throughout the manuscript, the term precipitation refers to total precipitation, which includes both rainfall and snowfall. The term '*rainfall'* is only used in relation to Fig. 6, where we specifically show liquid precipitation to illustrate the surface impacts of the ARs over the SEG and BKS regions. We have added a sentence to the manuscript to clarify the term: *'In line with the ERA5 variable definition, here, precipitation refers to the combined total of rain and snow.'* See lines 111-112 on page 4.

Q: Lines 126 – 131: More of a clarification question, since it is not mentioned prior to this point, do both ARs of interest move directly over the 'Met City' observation site? If not, how close does each system get?
A: Both ARs pass directly above the RV Polarstern on their poleward propagation, which makes the in-situ measurements so valuable for this study. To clarify this, we have made a small modification to the relevant sentence at the end of the introduction to explicitly note that both ARs reached the ship. The revised sentence now reads '*These ARs coincided with the Multidisciplinary Drifting Observatory for the Study of Arctic*

Climate (MOSAiC) expedition (Nicolaus et al., 2022; Shupe et al., 2022) with both passing directly over the research vessel (RV) Polarstern, which thus provides unique in-situ measurements.' See lines 77-79 on page 3.

Q: Line 414: Please add a space in "align,indicating", such that there is a space between the comma and the word "indicating".
A: Thanks for noting this. The typo has been corrected.

Point to consider:

When studying ARs entering the central Arctic basin, the use of additional ARDTs can provide further insights into AR characteristics. Historically, the tARget suite of algorithms tends to do a better job at capturing ARs closer to the midlatitude storm track, with tARget V4 receiving significant modifications for improved polar AR detection. With that said, other algorithms have been developed (e.g., Wille vIVT [Wille et al. 2021: https://agupubs.onlinelibrary.wiley.com/doi/10.1029/2020JD033788]) to capture meridionally propagating ARs that might reach the central Antarctic and Arctic regions and that deviate from the mid-latitude storm track. For this study, did you explore how the results change through the use of AR detection algorithms that differ in their general method of AR detection? Adding more than one ARDT to this study is not needed; this is just a curiosity I had.
A: Thank you for this thoughtful question. In this study we only used tARget v4, which consistently captures both ARs examined here. Both AR events are unambiguously strong and coherent features across multiple diagnostics (e.g., integrated vapour transport, moisture flux convergence, synoptic structure). Their presence and evolution are also directly confirmed by in-situ observations from RV Polarstern. This gives us high confidence that the AR identification does not depend sensitively on the choice of ARDT.
We acknowledge that ARDTs can differ substantially in their sensitivity to ARs propagating into high latitudes. Tools such as Wille vIVT were specifically developed to improve the detection of polar ARs, whereas tARget is relatively permissive in these environments (Shields et al., 2018; Rutz et al., 2019). In this study, however, the ARDT is primarily used to define an AR mask every six hours for initialising LAGRANTO trajectories, which are later subselected based on their thermodynamic properties. A more permissive detection is therefore advantageous, as it ensures that all potentially relevant air masses are included, reducing the risk of missing important contributions due to overly restrictive AR identification.
Comparing multiple ARDTs is beyond the scope of this work, but we agree it is an important direction for future studies, particularly for ARs reaching the high Arctic and for understanding uncertainties in their climatological and future impacts in polar regions.

Reply on RC2

Q: Line 26: The increases in AR frequency over the Arctic are not spatially uniform, with faster increases over the Atlantic sector (Ma et al., 2024a).

A: We thank the reviewer for this comment. We have incorporated the remark as follow: '*However, these trends exhibit substantial regional variability (Wang et al., 2024; Zhang et al., 2023), with AR frequency over the North Atlantic increasing at roughly twice the rate as over the Pacific in recent decades (Ma et al., 2024a).*' See line 40-42 on page 2.

Q: Line 211: 'Coinciding' is not very accurate here. It seems that Q2m begins to decline sharply only after precipitation returns to ~0. Please explain why the decline in Q2m lags behind changes in precipitation.

A: To address this comment, we have rewritten the relevant part as follows: '*A spike in total precipitation occurs while the Eurasian AR remains above the ship on 16 April (Fig. 3e), followed by a sharp decline in Q2m due to the removal of atmospheric moisture through precipitation, and accompanied by a marked decrease in SEB.*' See line 241-243 on page 11.

Q: Fig. 2a: The results shown here are consistent with the findings of Ma et al. (2024b) (see their Fig. 10). Arctic ARs are usually driven by a cyclone–anticyclone couplet. This couplet can be further divided into a high-pressure-dominant regime (associated with the Siberian AR), with a relatively weak low-pressure system to the left, and a low-pressure-dominant regime (associated with the Atlantic AR), with a relatively weak high-pressure system to the right. I think the authors should provide additional discussion in the Introduction on the flow regimes that drive Arctic AR formation. This would give readers more context for interpreting the results presented in this study.

A: We thank the reviewer for this comment and for drawing our attention to the study by Ma et al. (2024b). In response, we have expanded the Introduction section to include a description of the flow regimes associated with Arctic ARs, as well as a brief classification of the cyclone-anticyclone couplets driving the Atlantic and Eurasian ARs. The revised text reads:

'*Further, three distinct circulation patterns driving Arctic ARs have been identified: a dipole pattern, featuring high (low) pressure anomalies on the east (west) side of the AR; an anticyclone-dominated regime, characterised by a strong, persistent anticyclone on the east side of AR with a weak cyclone on the west; and a cyclone-dominated regime, characterised by a pronounced cyclone on the east side of the AR and weaker anticyclone on the west side (Ma et al., 2024b).*' See lines 32-36 on page 2.

‘*This circulation pattern is consistent with the cyclone-dominant regime identified by Ma et al. (2024b).’* See lines 221-222 on page 9.

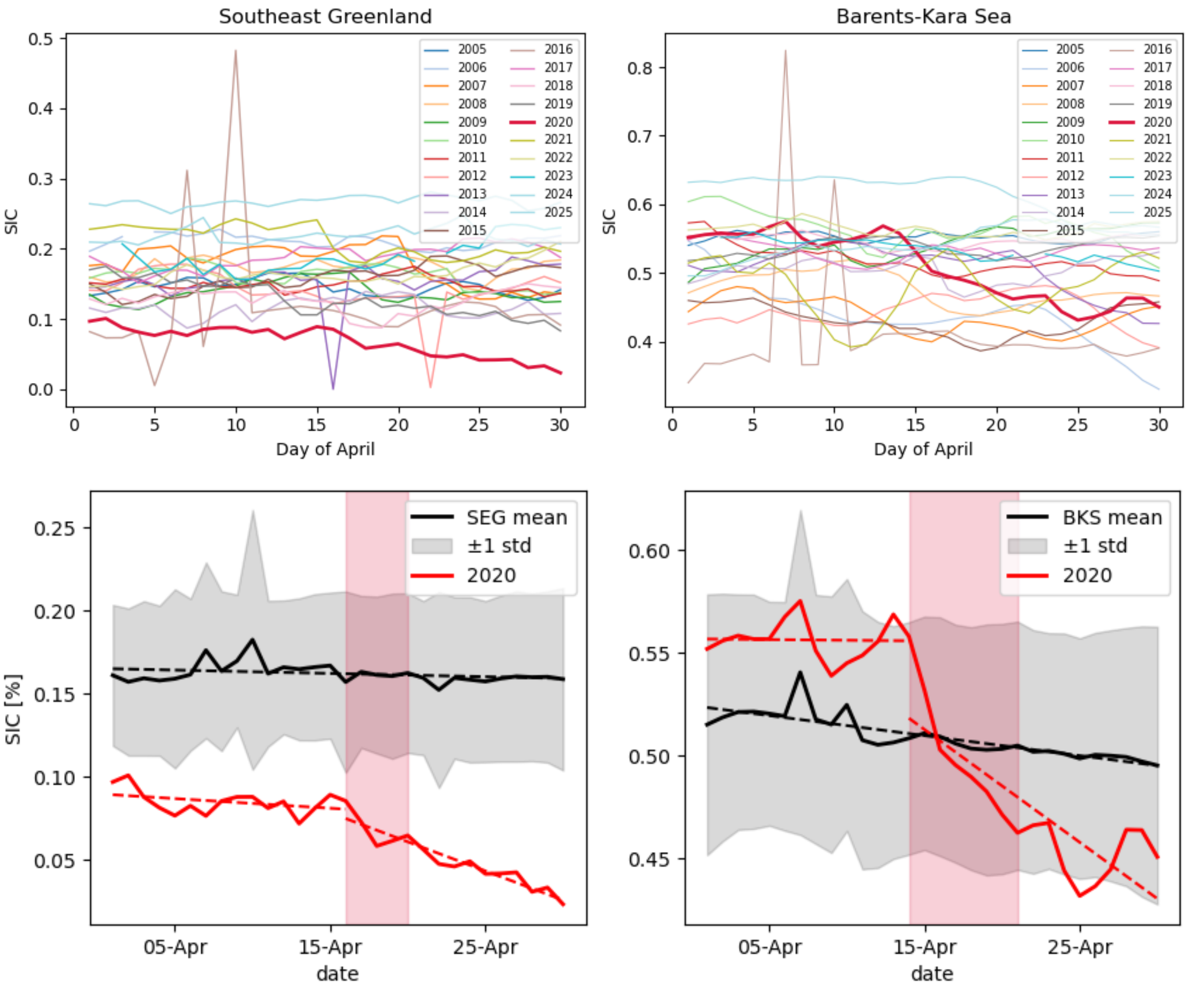
‘*This cyclone–anticyclone couplet corresponds to the anticyclone-dominated regime, which was the most common, accounting for approximately 40% of the events analysed by Ma et al. (2024b) and linked to the strongest and most spatially extensive surface warming anomalies.*’ See line 226-229 on pages 9-10.

Q: Fig. 5b: Sea-ice concentration decreases of comparable magnitude can also be observed in the marginal sea-ice regions of the Pacific sector. However, ARs were not observed in those regions. Is it possible that the sea-ice reduction shown in Fig. 5b is simply driven by the seasonality of sea-ice melt? Please also examine the sea-ice concentration differences between 12 April and 22 April in years when no AR event influenced these regions.

A: During the analysed period, a third Arctic AR occurred over western Canada where negative SIC changes in the Pacific sector can be seen in Fig. 5b. This AR was not included in our analysis, as it did not pass over the MOSAiC site, and we therefore lack the in-situ measurements required to study it consistently alongside the other two AR events. The SIC reductions in the Pacific sector during this period may be linked to this additional AR, though we acknowledge that SIC variability is influenced by many factors, including ocean temperature anomalies, wind speeds, and preceding sea-ice conditions, and it is beyond the scope of this study to fully explain all elements of this variability. We have clarified this point in the revised manuscript and added a sentence acknowledging that the impact of ARs on sea-ice conditions needs more detailed investigation in future studies: ‘*Additionally, the impact of ARs on sea ice variability requires more detailed investigation, given the many interacting factors that govern sea ice change.*’ See lines 479-480 on page 24.

9To place the SIC changes in context, addressing the latter part of the above comment, we compared SIC for April 2020 to the 2005–2025 climatology over the SEG and BKS regions (see both figures below). In SEG, SIC in April 2020 is anomalously low, falling below one standard deviation of the mean. SIC declines slowly at the start of the month, but an accelerated decrease is apparent following the AR event. In BKS, by contrast, SIC is initially above the climatological mean in early April 2020 before undergoing a rapid decline during the AR event, falling from 0.56% on 14 April to 0.43% on 25 April, thus, markedly faster than the gradual climatological decline.

We have added a sentence to the manuscript, discussing these points: ‘*SIC gradually decreases and remains anomalously low throughout the month, falling below the ± 1 s.d. range of the April 2005–2025 climatology (not shown). (…) While SIC is above the climatological mean in early April, a rapid and exceptional decline is observed during the AR period compared to the typical cycle (not shown).*’ See lines 295-305 on pages 13-14.

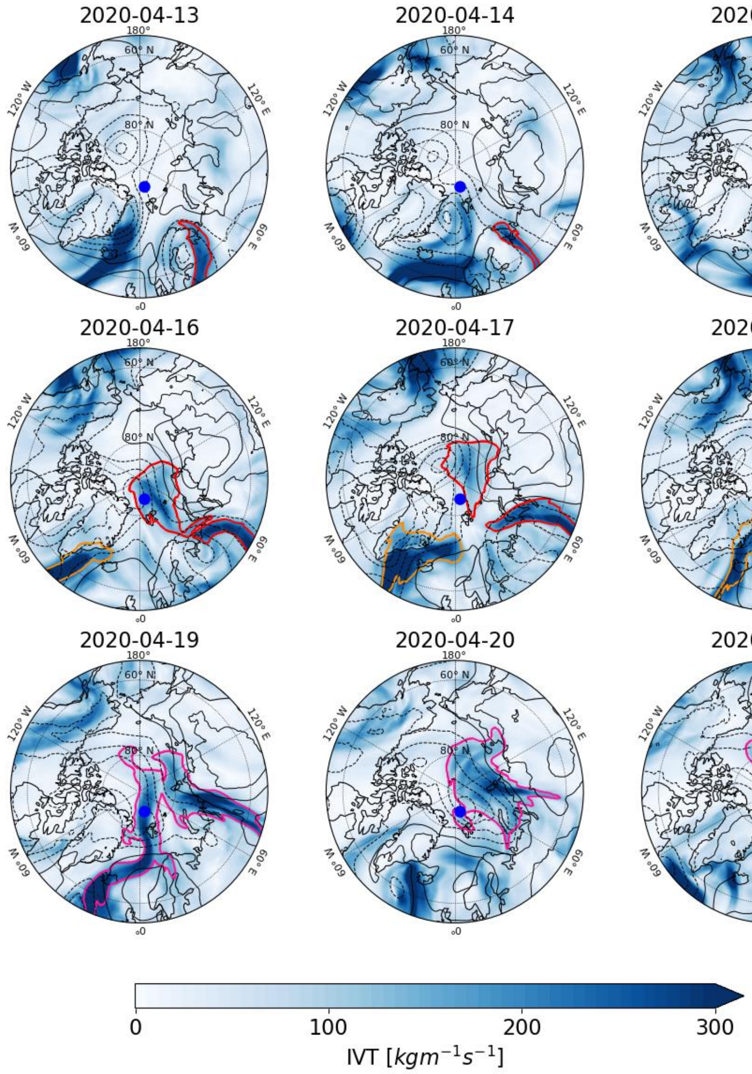


Q: Fig. 6c: What drives the precipitation peaks prior to the occurrence of ARs? Are they also driven by extreme moisture-transport events that are not captured by the Guan and Waliser (2024) AR detection algorithm? I recommend that the authors also plot IVT evolution in Fig. 1 using shaded contours and use line contours to indicate SLP anomalies. This would allow readers to assess whether these precipitation peaks are also associated with enhanced moisture transport.

A: Thank you for this comment. The precipitation peaks prior to the main AR events are indeed associated with ARs in the Guan and Waliser AR catalogue. Specifically, the catalogue identifies ARs over SEG on 05-06 April, 12-13 April and 21-22 April, which correspond directly to the spikes in precipitation visible in Fig. 6c. We have added a brief explanation of this in the revised figure caption and main text: '*The time series further reveal that notable precipitation and rainfall events occur outside the period when the ARs are located over SEG, coinciding with other Arctic ARs passing over the region on 05–06, 12–13, and 21–22 April (not shown).*' See lines 298-300 on page 13-14.

We have made a figure with IVT as shaded contours and MSLP anomalies as line contours (see figure below) following the reviewer's suggestion. This additional plot clearly shows that the precipitation peaks on 13 and 21 April over the SEG region do indeed coincide with high IVT. While the Guan and Waliser catalogue identifies them as ARs, we have only selected those AR contours that correspond to the Arctic ARs that are the focus of the present study. Including all detected ARs at each timestep would substantially overcrowd the figure, particularly given that the Guan and Waliser algorithm is relatively permissive compared to other AR detection tools, with multiple ARs commonly identified simultaneously over high latitudes (Shields et al., 2018; Rutz et al., 2019).

The figure shown below depicts enhanced IVT over multiple regions in the high latitudes such as over Alaska and the Atlantic. Including this figure in the main manuscript would shift focus away from the ARs analysed here. Further, as the first section of the results centres on the synoptic-scale cyclone and anticyclone evolution that steers the two ARs into the Arctic and their extreme nature, we retain MSLP as filled contours in Fig. 1.



Q: Lines 267-268: Based on Fig. 6d, precipitation starts to increase and peaks after the passage of the AR.

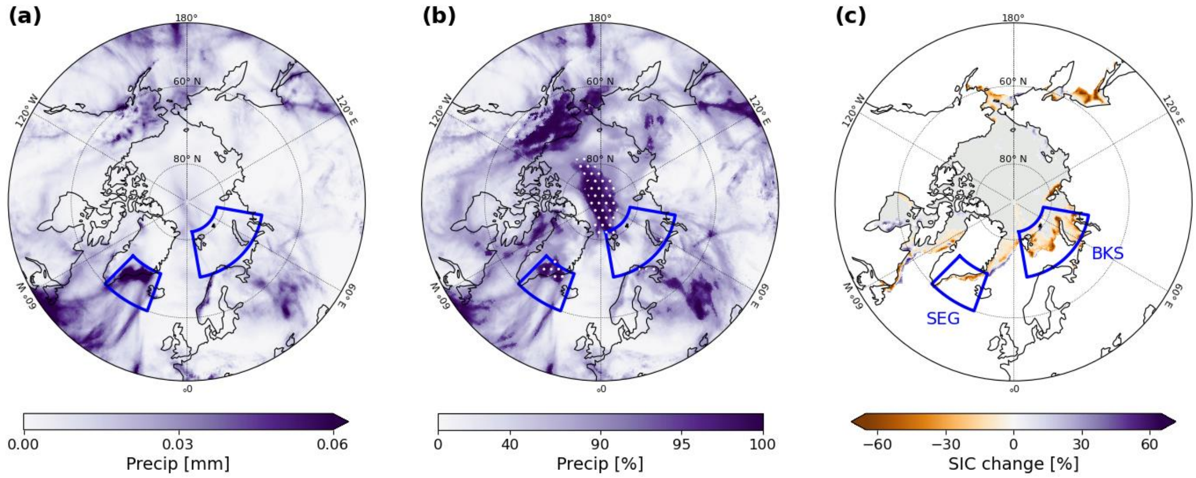
A: We thank the referee for pointing this out. The sentence has been altered as follows: '*Following the AR retreat, precipitation increases substantially.*' See lines 308-309 on page 14.

Q: Fig. 9 caption: Should be "moisture uptake minus the absolute magnitude of moisture loss"?
A: The caption has been modified for the respective subplots of figures 9 and 12 according to the suggestion and now read: '*Moisture uptake minus absolute loss*'.

Q: Line 346: I can see the strong moisture loss in the figure. However, I don't see how strong upward motion is reflected in the figures. Additional explanations might be helpful here.
A: We thank the referee for this comment. The sentence has been modified as follows: '*Moisture loss accompanied by upward motion also occurs along the Atlantic pathway towards Iceland (Fig. 12b,d). Additionally, strong moisture loss and upward motion is shown over the Greenland coast.*' See lines 388-389 on page 19.

Q: Fig. 5: I suggest that the authors also plot the spatial distribution of precipitation intensity. This would help readers better understand the magnitude of extreme precipitation associated with Arctic ARs.
A: When preparing Fig. 5, we carefully considered how to best visualise extreme precipitation associated with the Arctic ARs, noting that precipitation in the high latitudes can be classified as an extreme event despite its small absolute magnitude. This issue became evident when examining precipitation during the target period over the central Arctic. Plotting the absolute precipitation amounts or cumulative totals for the target period 15-21 April 2020 (has now been added as panel a to Fig. 5, also see below), shows that the total precipitation over the central Arctic is of very small magnitude (<0.03 mm) in comparison to that over lower latitudes. Similarly, precipitation anomalies in polar regions are typically modest because the climatological precipitation rates there are very low and deviations from the climatological mean still translate to small absolute differences. For this reason, maps of precipitation intensity can be difficult to interpret in the Arctic context.
This was the reasoning behind our decision to plot the gridded precipitation percentile for the target period relative to all 7-day accumulated precipitation values for April 1979–2023. We further used a specific colour bar with a custom centre point to draw the reader's attention to high percentiles, i.e. extreme precipitation occurrences. This approach allowed us to highlight how unusual the observed precipitation over the central Arctic was with percentiles exceeding the 90th percentile.
Nonetheless, in response to the reviewer's recommendation, we have included the cumulative precipitation field as an additional panel to Fig. 5 to provide readers with a

clearer visual representation of the spatial distribution of precipitation associated with the analysed AR events.



The revised manuscript now reads: ‘*Figure 5a shows that precipitation is particularly enhanced along the southeastern coast of Greenland, when accumulated over the target period, highlighting the key role of orographic uplift from the steep topography of Greenland in driving extreme precipitation events. In contrast, precipitation over the central Arctic remains relatively low compared to lower latitudes. When expressed as percentiles relative to the climatological distribution at each grid point (Fig. 5b), however, precipitation across the central Arctic is highly unusual, exceeding the 90th percentile and coinciding with areas where ARs persisted for at least three days (Fig. 4a). Precipitation along the southeastern Greenland coast is also highly anomalous relative to its climatology.*’ See lines 274-279 on page 12.

Q: Fig. 7: Please explain how you calculated this spatial density distribution for parcel trajectories. This can help readers better interpret the results.

A: We have expanded on the explanation of the spatial density distribution plots. The figure caption for Fig. 7 now reads: ‘(…) *(b) Spatial density distribution of nTpΘ trajectories, obtained by binning all trajectory longitude–latitude positions into 2 ° × 2 ° grid cells and computing a normalised two-dimensional histogram. Values represent the probability density of trajectory positions*.’

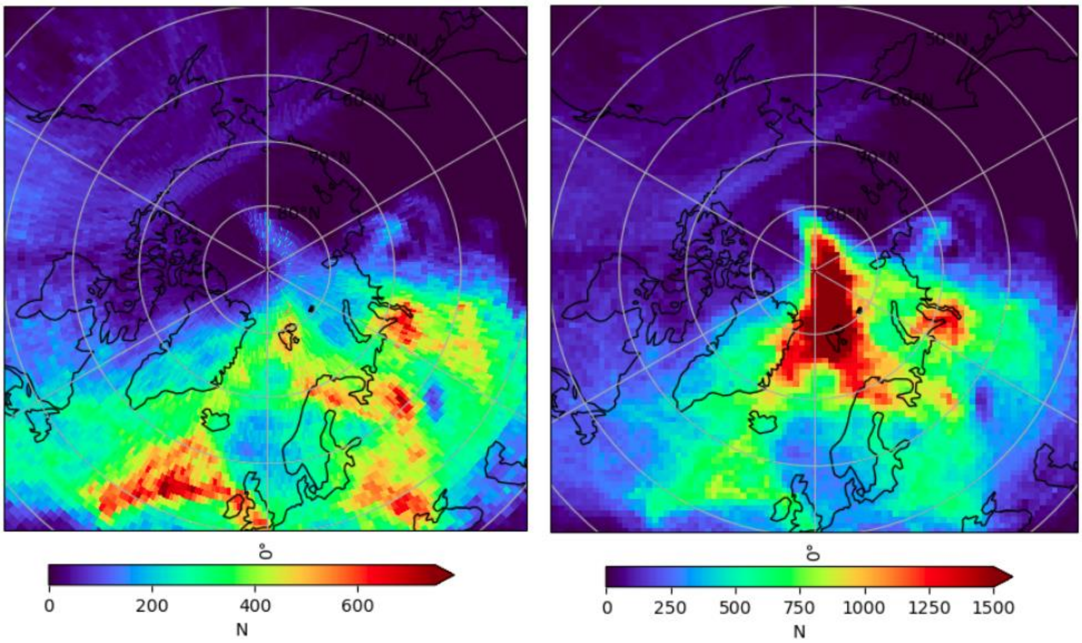
Q: Fig. 10: Since all these parcels are released in central Arctic, shouldn’t central Arctic have the highest density distribution?

A: We thank the reviewer for pointing this out. Indeed, the central Arctic has the highest trajectory density, as this is where all parcels converge over a relatively small area. For Fig. 10, we computed densities on a 2°×2° latitude-longitude grid. When visualized on a Plate Carree projection, the bins appear equal in size, but their physical area is smaller at higher latitudes, effectively reducing the density at high latitudes (less parcels are counted in bins of smaller size). Plotting the density field on a North Polar

Stereographic projection clearly shows the effect of shrinking bin sizes with latitude (see figure below, left panel). This is the reason why the central Arctic does not appear as the region of highest density in Fig. 10.

To look further into this, we redefine the grid to consist of equal-sized bins in the North Polar Stereographic projection. In this representation, the central Arctic clearly shows the highest density compared to lower latitudes, reflecting the actual concentration of parcels. Note that now the bins appear to represent the same area in the NorthPolarStereo projection, but bins at lower latitudes are now smaller in physical size. Also, keep in mind that both figures below include all trajectories reaching the central Arctic with precipitation ±90th percentile, without any additional grouping based on ΔT or Δθ.

As the difference in density is somewhat striking, we will redo Figures 7 and 10 by taking the actual bin size into account. For now, we have added a sentence to the figure caption of Fig. 7 to clarify this binning/projection issue: *'Note that grid cell area decreases with latitude, such that bins at higher latitudes are smaller than those at lower latitudes. As a result, lower-latitude bins tend to contain more parcels and exhibit higher apparent densities, while higher-latitude bins contain fewer parcels and appear less dense.'*



Q: Fig. 12: Please explain why there is a lack of moisture loss over the central Arctic where extreme AR precipitation occurs, and parcels are released.

A: We thank the reviewer for this comment. The apparent lack of moisture loss over the central Arctic reflects the very small absolute precipitation amounts in this region, consistent with the reviewer's earlier observation regarding Fig. 5 and the need to use percentiles rather than absolute values. Although the central Arctic experienced unusually high precipitation relative to its climatology, the actual amounts remain low compared to lower-latitude regions.

As shown in Fig. 12c, some moisture loss does occur north of 80°N between Greenland and Svalbard. However, although this moisture loss is unusual for this region, its magnitude is relatively small (up to ~10 g kg^{-1}) compared to the substantially larger moisture losses occurring further south along the two transport pathways. Consequently, the central Arctic appears to exhibit comparatively weak moisture loss in the spatial distribution. We have added a sentence to discuss this: *'In the Arctic, moisture loss is observed west of Svalbard, and although highly unusual for the region, it remains relatively small in magnitude compared to the larger losses occurring at lower latitudes.'* See lines 397-399 on page 20.

Q: Lines 364-365: If that is the case, why not track the parcels backward in time for more than 7 days?

A: We thank the referee for this comment, which helped us improve the discussion of moisture uptake within the Eurasian AR. We have modified the sentence to read: *'The Eurasian AR derived its moisture from continental Eurasia (Fig. 12). While moisture uptake was most pronounced over central and eastern Europe, a secondary uptake region is evident east of the Ural Mountains over western Siberia. The close spatial alignment between moisture uptake and loss regions suggests that a substantial fraction of moisture is locally recycled within the AR (Nusbaumer and Noone, 2018), indicating that parcels already carried elevated moisture content when being incorporated into the AR airmass and highlighting the role of long-range transport in sustaining AR moisture content.'* See lines 452-456 on page 23.

LAGRANTO back trajectories are computed for 9 days. The trajectory length used in the manuscript is then selected based on the AR lifecycle (Atlantic or Eurasian) and the parcel property evolution (Fig. 11 for different trajectory lengths; not shown in the manuscript), as described in the Methods section lines 183-187 on pages 6-7. Extending the trajectories further did not provide additional insight, as the key features of the parcel evolution remain unchanged.

Q: Line 366: Should be decreasing pressure.

A: We thank the referee for pointing this out. The text has been corrected.

Q: Lines 398–400: This is consistent with the Arctic AR trajectory-clustering results shown in Fig. 7d of Ma et al. (2025). They show that ARs that travel along the U.S. East Coast or the western Atlantic before entering the Arctic through the Atlantic pathway tend to be associated with enhanced moisture uptake from the warm waters of the Gulf Stream

A: We thank the referee for this suggestion. We have modified the relevant section as follows: '*These parcels originate south of 40°N and travel northward along the eastern* *coast of the USA, drawing moisture predominantly from the warm waters of the Gulf Stream (Fig. 9). This aligns with previous studies showing that Arctic ARs of subtropical origin propagating through the Atlantic sector acquire moisture from the western North Atlantic (Ma et al., 2025).'* See lines 439-442 on page 23.

Addendum to Reply on RC2

We thank reviewer #2 for their thorough and helpful comments. In response to the comment below, we have revised the trajectory density calculations for Figs. 7 and 10 to account for the physical area of grid cells, which varies with latitude. For consistency, Figs. 9 and 12 have also been updated to express moisture uptake and loss per km^2. While the changes have little impact on the Greenland coast case (Figs. 7 and 9), the central Arctic case (Figs. 10 and 12) is notably affected with high latitude areas playing a more prominent role in the revised figures. Three of the comments by reviewer #2 require revisiting, as the changes impact our previous responses:

Q: Fig. 7: Please explain how you calculated this spatial density distribution for parcel trajectories. This can help readers better interpret the results.
A: The caption for Fig. 7 now reads: '(...) *(b) Spatial density distribution of nTpθ trajectories, obtained by binning all parcel positions along their trajectories into 2°× 2° grid cells. Values represent the probability density per km^2 of parcel positions, normalised by the total number of positions and the physical area of each grid cell, thereby accounting for the decrease in grid-cell area with increasing latitude.'*

Q: Fig. 10: Since all these parcels are released in central Arctic, shouldn't central Arctic have the highest density distribution?
A: We have now modified the way the trajectory densities are computed by taking all latitude-longitude positions of the parcels along their trajectories and binning them into 2°× 2° grid cells. The values are then normalised by the total number or trajectory points and the area of the cells in km^2. This way, we account for smaller grid cells at high latitudes, and the central Arctic correctly shows the highest parcel densities, consistent with parcels being released there.

Q: Fig. 12: Please explain why there is a lack of moisture loss over the central Arctic where extreme AR precipitation occurs, and parcels are released.
A: The apparent lack of moisture loss over the central Arctic in the previous figures was an artefact of not accounting for the decreasing physical size of grid cells at high latitudes. Smaller cells accumulate less moisture loss in absolute terms, leading to an underrepresentation of high-latitude precipitation. After normalising by grid-cell area (per km^2), enhanced moisture loss over the central Arctic is evident and consistent with

the diagnosed upward motion of air parcels. The text has been altered to state: ‘In the Arctic, enhanced moisture loss is observed in the vicinity of Greenland and Svalbard consistent with upward motion of air parcels.’ See lines 397-398 on page 19.

Reply on RC3

General remarks:

Q: For the drivers of the two ARs: the authors emphasized the steering impacts of a cyclone-anticyclone couplet. Although the two high/low MSLP centers in between in Fig. 2a have also been analyzed, but it seems that their roles are secondary compared to those two highlighted in Fig. 2b-c. I was wondering whether the cyclone-anticyclone couplet is a must for intense ARs to penetrate into the Arctic. Also, why the anomalous cyclone is important for the Atlantic AR and the anomalous anticyclone for the Siberian AR? Are they random case-dependent or more like common features?

A: We have expanded on the importance of cyclone-anticyclone couplets in driving Arctic ARs. Further, reviewer #2 has suggested to include a brief description of different flow regimes associated with Arctic ARs. In their study, Ma et al. (2024) have applied a k-means clustering algorithm to the large-scale MSLP pattern associated with extreme warming events in the Arctic linked to ARs, and found a dipole pattern, a cyclone-dominant pattern and an anticyclone-dominated pattern to be linked to the events. This puts our study into a broader context, as we find that the Atlantic AR is associated with an extremely anomalous cyclone, thus a cyclone-dominated regime, while the Eurasian AR is primarily driven by an exceptional anticyclone. We have added a description of the regimes to the introduction which now reads: ‘*Previous studies have emphasised the role of cyclone–anticyclone couplets in steering ARs into the Arctic (Gong et al., 2024). In the Atlantic sector, ARs are typically linked to cyclones that develop and deepen near Greenland, coupled with anticyclones over Scandinavia and Siberia (Papritz et al., 2022; Woods et al., 2013). Further, three distinct circulation patterns driving Arctic ARs have been identified: a dipole pattern, featuring high (low) pressure anomalies on the east (west) side of the AR; an anticyclone-dominated regime, characterised by a strong, persistent anticyclone on the east side of AR with a weak cyclone on the west; and a cyclone-dominated regime, characterised by a pronounced cyclone on the east side of the AR and weaker anticyclone on the west side (Ma et al., 2024b).’* See lines 30-36 on page 2.

Further, when characterising the cyclone-anticyclone couplets shown in Fig. 2, we have added the following sentences to the description: ‘This circulation pattern is consistent with the cyclone-dominant regime identified by Ma et al. (2024b). *(…) This cyclone–anticyclone couplet corresponds to the anticyclone-dominated regime, which was the most common, accounting for approximately 40% of the events analysed by Ma et al. (2024b) and linked to the strongest and most spatially extensive surface* *warming anomalies.'* See lines 221-229 on pages 9-10.

Q: According to the distinct pathways, the Atlantic AR have strong impacts on Greenland and central Arctic, whereas the Siberian AR on Eurasia and also central Arctic. These are evident results that have been revealed by previous studies. I would like to see some further discussion about comparing the strength of Siberian and Atlantic AR impacts. For example, which of them could exert greater surface impacts on the central Arctic (e.g., the Atlantic AR seems to bring about more precipitation over the central Arctic in Fig. 3b)? In this case, it is difficult to isolate the impacts of the two ARs because they ended up merged together. But the simultaneous occurrence of the Atlantic and Siberian ARs would not always take place, very likely I supposed, thus the difference between them is worth being discussed.
A: Thank you for raising an important point about quantitively assessing the relative strengths of Atlantic and Siberian AR impacts on the central Arctic. The two ARs had distinct characteristics and regional impacts that are worth highlighting. In our study, we show that the Eurasian AR was more strongly associated with widespread surface temperature anomalies across the Eurasian landmass (Fig. 4), while the Atlantic AR was characterised by more abundant moisture transport, producing more intense precipitation along the Greenland coast and over the central Arctic (Fig. 3e, Fig. 5a,b). Both ARs contributed to increased cloud cover, enhanced downward longwave radiation, and warming at the MOSAiC site (Fig. 3), and coincided with notable sea ice retreat in the Barents-Kara Sea and along the south-eastern coast of Greenland (Fig. 5c).
However, our study represents a case study in which the Atlantic and Siberian ARs evolve and merge into a joint system; the two ARs interact and cannot be cleanly separated in space or time. We are therefore not able to isolate their independent contributions in a robust way for this event. A systematic comparison of Atlantic versus Siberian AR impacts on the central Arctic would require a larger event sample and a dedicated analysis framework that properly separate these two types of ARs. Their impact may also involve seasonal variations, which falls outside the scope of this study but represents an interesting direction for future work.

Q: I suggest, if there is any, the authors could also provide some simple characteristics of similar/comparable Atlantic or Siberian ARs in the global AR database, which could help support the findings. This is also a potential way to scope with the first two concerns.
A: We agree that comparing our case with similar Atlantic or Siberian ARs from a global AR database could in principle provide useful context. However, this type of assessment would require identifying a suitable set of comparable events and analysing their structure, trajectory characteristics, evolution and surface impacts using consistent criteria. Such an analysis would go beyond the scope of this study.

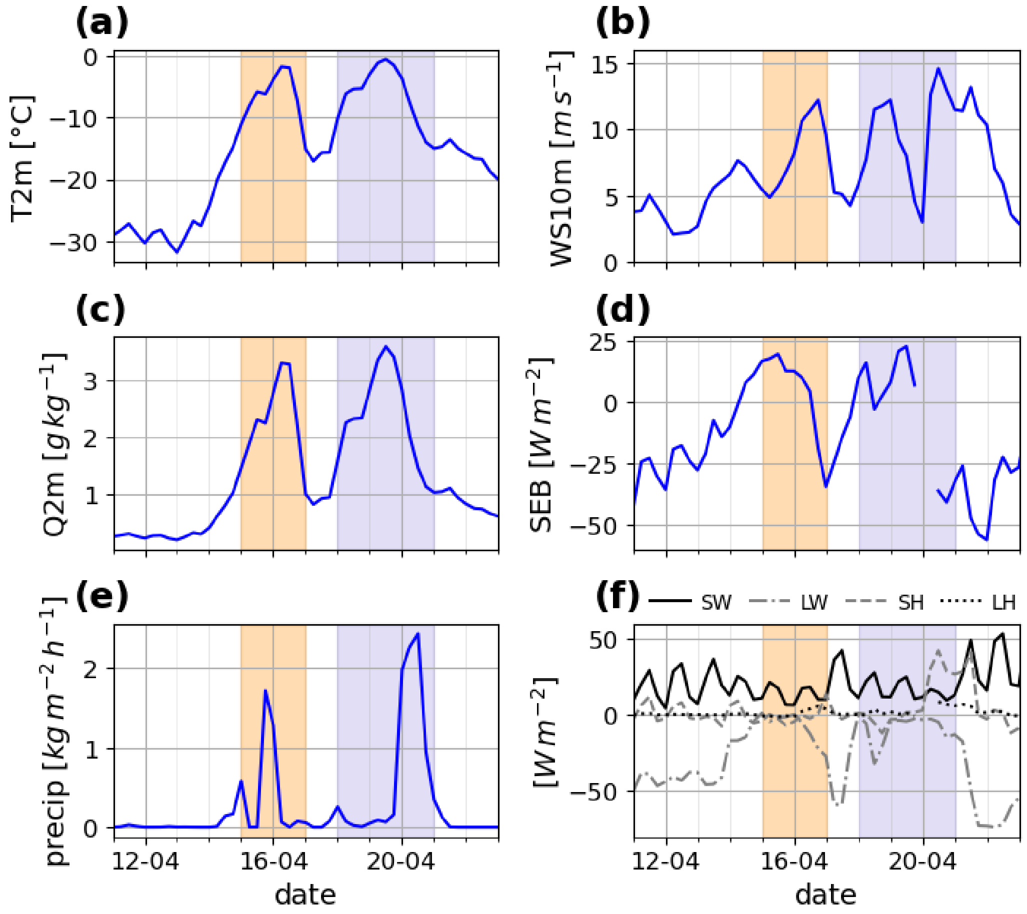
Specific remarks:

Q: L31-32: I don’t understand why the “observed increase …” is in line with “projections”? Do the projections here mean future predictions or historical simulations?

A: By ‘projections’ we mean future projections. This has been added to the sentence, see line 39 on page 2.

Q: L54: Since the strong near-surface winds have been mentioned here, I suggest the effect of the surface wind should also be discussed, besides the results in Fig. 6.

A: We thank the reviewer for this comment. We have added the 10m wind speed (WS10m) as an extra panel to Fig. 3 (see figure below). The modified text now reads: *‘The approach of the Eurasian AR is marked by a stark rise in T2m (Fig. 3a), increasing from about -30°C on 13 April to just below 0°C on 16 April. This warming is accompanied by higher WS10m (Fig. 3b), a pronounced increase of roughly 3 g kg^{-1} in Q2m (Fig. 3c), and a steady increase in SEB (Fig. 3d) from negative to positive values. (…) Notably, the rise in T2m, WS10m, Q2m, and SEB begins 1-2 days prior to the AR reaching the MOSAiC site, indicating that the airmasses associated with the AR were gradually influencing surface conditions before its core arrival. (…) WS10m decreases to about 5 m s^{-1} while T2m drops rapidly by about 15°C between 16-17 April, yet remaining well above pre-Eurasian AR temperatures*
(…) Strong WS10m accompany the arrival of the Atlantic AR (Fig. 3b) while SEB (Fig. 3d) also increases to high positive values, reflecting enhanced energy influx to the surface.’ See lines 232-250 on pages 10-11.



Q: L87: The Atlantic AR has not shown up on 15 April within the Arctic Circle.

A: We thank the reviewer for pointing this out. We have clarified the definition of the target period to note that although the Atlantic AR enters the Arctic Circle on 16 April, the period 15–21 April captures the main phase of the event and the combined influence of both ARs within the Arctic Circle. The revised text reads: '*We further define 15–21 April 2020 as the target period, representing the main phase of the event during which the two ARs influenced Arctic conditions, with both systems located within the Arctic Circle (north of 66.34°N) for the majority of this period.*' See lines 100-102 on page 4.

Q: L99-105: Why the calculations of the reference distribution are different for different variables (MSLP, T2m, and precipitation)? It sounds a bit complicated and subjective (how about changing the length of days to include more or fewer days?). It would be better if some of them could be unified.

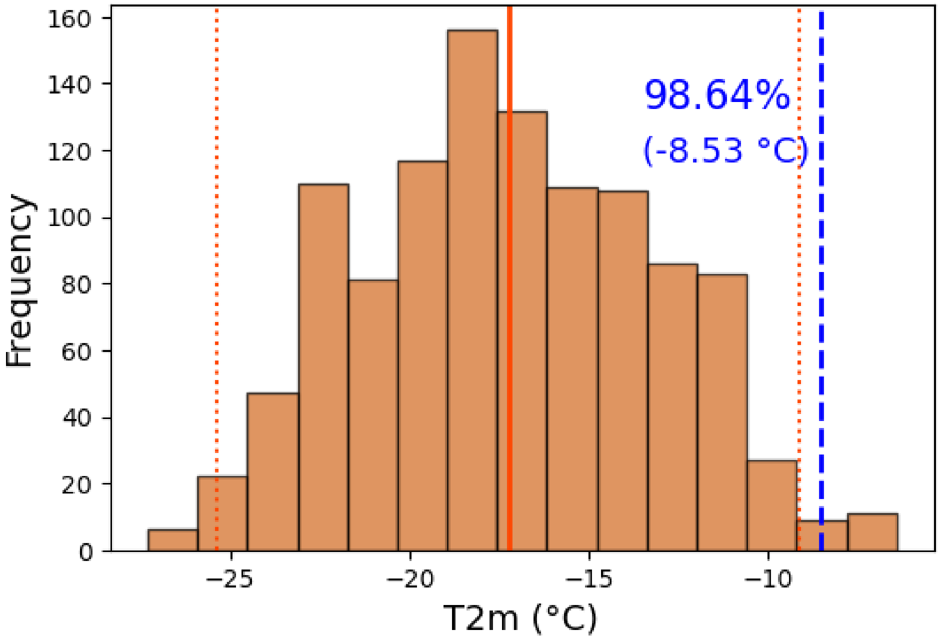
A: We thank the reviewer for this comment. While the technical details differ by variable, the same underlying methodology is used in all three analyses. In each case, anomalies or accumulated values for the target period are evaluated against a reference distribution based on April conditions over the same period (1979–2023), constructed using a 7-day moving window. The variable-specific choices reflect their different physical characteristics and impacts. For MSLP, we average over large, predefined regions to capture the large-scale circulation anomalies that drive the poleward intrusion of the respective ARs. For T2m, we average over areas influenced by the ARs for an extended period so that we can represent their longer-lasting temperature effects. For precipitation, we use grid-point values to capture its strong spatial variability and to show how unusual the accumulated totals were in the central Arctic compared with the climatology.

We have added a clarifying sentence at the start of the paragraph that now reads: '*To assess how unusual the atmospheric conditions associated with the Arctic ARs were, we determine anomalies and accumulated values during the target period against reference distributions constructed using a 7-day moving window for April 1979–2023. The same general framework is applied to all variables, although the spatial aggregation differs depending on the variable.*' See lines 114-117 on page 4.

Q: Figure 4b: It would be more meaningful also providing the PDF of absolute T2m, like that in Fig. 3a. Or just provide readers the climatology mean of all 7-day mean T2m, helping contextualize the anomaly magnitude.

A: We thank the reviewer for this helpful suggestion. Following this comment, we computed the PDF of absolute 7-day mean T2m over the Arctic region where the ARs persisted for at least three days (see figure below). The dashed blue line indicates the T2m value during the target period, while the solid red line denotes the mean of the distribution and the dotted lines represent ±2 s.d. The climatological 7-day T2m mean for April for this region is −17.2°C. The temperature during the AR event (−8.53 °C) is therefore highly unusual relative to the April distribution, corresponding to the 98.6th percentile and exceeding two standard deviations. This confirms that the absolute temperatures in the central Arctic during the AR event were exceptionally high for the season and supports the interpretation shown in Fig. 4b.

We have added the following sentence to the main text: '*Consistent with this, the corresponding absolute 7-day mean T2m value averaged over the same region reaches −8.53 °C, which is also exceptionally high relative to the April distribution, exceeding two standard deviations above the climatological mean (−17.2°C) (not shown).*' See lines 270-272 on page 12.



Q: L280: Differences "relative to their trajectory endpoints" more sound like the initial status minus the endpoint, but the authors actually mean the reverse.

A: We thank the reviewer for pointing this out and agree the wording could be confusing. We now define trajectory endpoints clearly in the Methods section as follows: '*Hereafter, we refer to a trajectory endpoint as the final location of an air parcel, from where the parcel is traced backward in time.*' See lines 181-182 on page 6.

Q: L302: The orographic precipitation augmentation by the steep topography over the southeastern Greenland is a key factor for the in-situ extreme precipitation in Fig. 5a. I suggest this should be mentioned more and in advance.

A: We agree with the reviewer's commet. Following a comment by reviewer #2, we have added a panel to Fig. 5 showing the absolute precipitation magnitude accumulated over the target period. It clearly highlights the strong precipitation along the southeastern Greenland coast. We have also added a sentence noting the role of topography in enhancing orographic precipitation. The revised text reads: '*Figure 5a shows that precipitation is particularly enhanced along the southeastern coast of Greenland, when accumulated over the target period, highlighting the key role of orographic uplift from the steep topography of Greenland in driving extreme precipitation events.*' See lines 274-276 on page 12.

Citation: https://doi.org/10.5194/egusphere-2025-6285-RC3

Reply on RC4 and RC5

Major/clarifying comments:

Q: The AR identification is based on Guan and Waliser (2024), who also employ a Lagrangian tracking framework. According to their tracking methodology, the Siberian AR event and the Atlantic AR event appear to be merged into a single AR event (if my understanding is correct). However, throughout the manuscript the two events are described as separate ARs. It would be helpful to include a brief clarification explicitly stating that, under the Guan–Waliser AR algorithm, these two ARs are identified as a single merged event, while they are analyzed separately in this study.
A: We thank the reviewer for this comment. The tARget algorithm identifies AR objects at individual time steps and tracks each AR object through space and time, with two AR shapes at adjacent time steps that spatially overlap being regarded as belonging to the same life cycle (Guan and Waliser, 2024). In this Lagrangian framework, the Eurasian and Atlantic ARs are tracked as individual objects until a merger occurs, i.e. an AR shape is identified that overlaps with the spatial footprints of both/multiple ARs from the previous time step. At this point, tARget v4 continues the life cycle of the AR that most closely matches the new shape and terminates the other. This results in a single merged AR object being identified over the Arctic during the latter stages of the life cycle.

Because the two ARs have different synoptic drivers, moisture origins, and regional impacts, we study them as separate events during their earlier stages and note that they subsequently merge in the Arctic. We have added a clarifying sentence to the methods section: '*As the two ARs merge over the central Arctic in the latter stages of their lifetimes, the tARget tracking algorithm identifies them as a single AR object for those time steps.*' See lines 163-164 on page 6.

Q: Regarding Figure 3: In April, decreases in net shortwave radiation associated with ARs can also contribute to the net surface energy budget (SEB), in addition to enhanced net longwave radiation (Zhang et al., 2025). It would be helpful to discuss the contribution of net shortwave radiation to net SEB, as net shortwave radiative appears to decrease during the two AR events shown in Figure 3e, which may help explain the slight decrease on net SEB on April 16.
In addition, prior to the arrival of the Siberian AR, net longwave radiation, 2-m temperature (T2m), precipitation, 2-m specific humidity (Q2m), and net SEB already show increases, while during the Siberian AR itself the net longwave radiation remains

relatively steady. Could the authors please elaborate on the atmospheric conditions preceding the arrival of the Siberian AR that may explain these features?
I also suggest computing T2m, precipitation, Q2m, and surface energy budget components (including longwave, shortwave, sensible, and latent heat fluxes) from ERA5 and comparing them with the MOSAiC in situ observations shown in Figure 3. This comparison could help readers to appreciate a broader spatial context and allow for an assessment of the consistency between the reanalysis and the MOSAiC observations.
A: We thank the reviewer for this comment and agree that the SEB components in Fig. 3 would benefit from further clarification. We have addressed the three points as follows: First, regarding the role of net shortwave radiation to the SEB, the slight decrease in net SEB during the second half of 16 April may be explained by the diurnal cycle of net shortwave radiation, as net longwave radiation and turbulent fluxes remained fairly steady during this period. We have added the following to the revised manuscript: '*Together with a reduced amplitude of the diurnal cycle of net shortwave radiation, the enhanced net longwave radiation suggests an increase in cloud cover. (…) As during the Eurasian AR, reduced net shortwave radiation is observed.*' See lines 238-254 on page 11.

Secondly, regarding the atmospheric conditions leading up to the arrival of the Eurasian AR, we have complemented the description of Fig. 3 with the following: '*Notably, the rise in T2m, WS10m, Q2m, and SEB begins 1-2 days prior to the AR reaching the MOSAiC site and indicates that the airmasses associated with the AR were gradually influencing surface conditions before its core arrival.*' See line 239-241 on page 11.

Finally, we appreciate the suggestion to compare ERA5 with the MOSAiC observations. However, a full evaluation of ERA5 against the in-situ MOSAiC observations would be beyond the scope of the present study, which focuses on the large-scale characteristics and impacts of the AR events. A detailed reanalysis validation would shift the paper away from this central aim. For this reason, we decide not to carry out such a comparison.

Minor comments:

Q: Lines 19–22: I recommend citing the canonical AR definition paper by Ralph et al. (2018).
A: We have added a reference to Ralph et al. (2018).

Q: Figure 1: Please consider using two distinct colors to clearly differentiate the Siberian AR from the Atlantic AR.
A: Thank you for this comment. Changing the colours of the AR outlines in Fig. 1 has also been suggested by referee #1 and we have selected three different colours to

indicate (1) the Eurasian AR, (2) the Atlantic AR and (3) the merged AR (see figure on page 3). The figure caption now reads: '*Red (teal) contours outline the shapes of the Eurasian (Atlantic) AR at 12:00 UTC of the respective days diagnosed from the tARget database. After the ARs merge, the contours are shown in pink.*'

Q: Figure 3 (title): Please specify that the in-situ observations refer to measurements from RV Polarstern.
A: The figure caption has been modified to '*MOSAiC in-situ observations taken at RV Polarstern for 11-23 April 2020.*'

Q: Line 145 (Section 2.5): Please provide additional details on the Lagrangian Analysis Tool (LAGRANTO v2.0) used in the parcel tracking analysis.
A: We agree that additional detail on the Lagrangian Analysis Tool (LAGRANTO v2.0) improves clarity in the Methods section. Following this comment and a related remark by reviewer #1, we have added the following sentence to better describe its capabilities and justify its use: *'While tARget v4 (see Sect. 2.4) includes Lagrangian feature tracking, it is limited to tracking the displacement of ARs over time, i.e. the propagation of a coherent pattern, which may move at a different speed and direction than the underlying airflow. LAGRANTO v2.0, by contrast, conducts air parcel tracking, computing full 3-D kinematic trajectories of individual air parcels that are essential for assessing sources and sinks of heat and moisture.'* See lines 167-171 on page 6.

Q: Lines 343–345: Figure 12 shows nTnθ, but the text refers to nTpθ. Please correct this inconsistency.
A: We thank the reviewer very much for pointing out this mistake. Fig. 12 shows nTpθ parcels that reach the central Arctic analogously to Fig. 9 for east Greenland. We have corrected the figure caption to read: '*Same as Fig. 9 but for 7-day back trajectories of nTpθ parcels from Fig. 10.*'

References:

Zhang, C., Cassano, J. J., Seefeldt, M. W., Wang, H., Ma, W., and Tung, W.: Quantifying the impacts of atmospheric rivers on the surface energy budget of the Arctic based on reanalysis, The Cryosphere, 19, 4671–4699, https://doi.org/10.5194/tc-19-4671-2025, 2025.

Guan, B. and Waliser, D. E.: A regionally refined quarter-degree global atmospheric rivers database based on ERA5, Scientific Data, 11, https://doi.org/10.1038/s41597-024-03258-4, 2024.

Ralph, F. M., Dettinger, M. C. L. D., Cairns, M. M., Galarneau, T. J., and Eylander, J.: Defining "Atmospheric river": How the glossary of meteorology helped resolve a debate, B. Am. Meteorol. Soc., 99, 837–839, https://doi.org/10.1175/BAMS-D-17-0157.1, 2018.

Reply on RC6

Minor overview comments:

Q: Some refinement and clarification about the climatological context for these AR events is needed. It appears that the claims of an "unprecedented event" (L84) and "unprecedented transport of heat and moisture into the region" (L384) are based on the previous analysis of Rinke et al. (2021), is that correct? If so, this should be stated clearly, and some further context for what was unprecedented about this event should be provided - i.e. it appears that Rinke et al. (2021) found that there were daily record highs of temperature, TCWV, and longwave radiation at the MOSAiC site relative to the ERA5 1979–2019 climatology on some of these dates? If so, while these daily record highs do confirm that this was an extreme event, I think that a wider net (e.g. monthly or seasonal climatology) would need to be cast to claim that this event was without precedent in the historical record.

A: We thank the reviewer for this comment and agree that the climatological context requires clearer explanation. The statements in the Introduction are indeed based on the analysis of Rinke et al. (2021). We have revised the text to make this explicit and to clarify that the reported record-breaking anomalies in moisture, outgoing longwave radiation, and surface temperature are defined relative to the climatology for the respective dates at the RV *Polarstern's* location based on the ERA5 reference period. The revised text now reads: '*Rinke et al. (2021) showed that these two Arctic ARs led to exceptional atmospheric conditions at the location of the ship, including record-breaking high moisture on 16, 19 and 20 April relative to the climatology for those dates, as well as the lowest outgoing longwave radiation ever recorded on 20 April. In addition, a rapid 20°C increase in surface warming resulted in record-breaking daily temperatures on 16 and 19 April.*' See lines 79-83 on page 3.

We agree that, while these daily record anomalies show that the event was extreme, they do not by themselves demonstrate that the event was unprecedented. To avoid misunderstanding, we have adjusted the wording, replacing '*unprecedented event'* with '*exceptional event'* (line 96) and '*unprecedented transport of heat and moisture'* with '*extraordinary transport of heat and moisture'* (line 425).

Q: On a similar point, the different climatological reference periods for the statistical calculations in Section 2.1 are a bit hard to follow. For example, why are there two sets of T2m anomalies (daily anomalies from the April mean climatology, and 7-day centered mean anomalies)?

A: We appreciate the reviewer for noting that climatological reference periods in Section 2.1 were difficult to follow. To improve clarity, we have slightly restructured this section. The first paragraph now focuses only on introducing ERA5, listing the variables used, and defining how anomalies are calculated relative to climatology. The second paragraph then describes how we assess the AR impacts.

Because the ARs persisted over the Arctic for an extended period, we examine anomalies in MSLP, precipitation, and T2m during 15-20 April 2020 relative to their distributions formed by all 7-day averages from April 1979-2023. This approach allows us to evaluate how unusual the event was over its multi-day duration, rather than on individual days. The relevant part of Section 2.1 now reads:

‘*To assess how unusual the atmospheric conditions associated with the Arctic ARs were, we determine anomalies and accumulated values during the target period against reference distributions constructed using a 7-day moving window for April 1979–2023. The same general framework is applied to all variables, although the spatial aggregation differs depending on the variable.*

For MSLP, we examine the persistent intensity of low- and high-pressure systems associated with the Arctic ARs at their respective locations. For this, we determine the 7-day mean MSLP anomaly field for the target period and define bounding boxes enclosing each weather system. For each box, we construct a reference distribution of 7-day mean MSLP anomalies for April 1979–2023. The percentile of the target period anomaly is then computed within this distribution.

A similar approach is applied to T2m to quantify the longer-lasting impact of the ARs on the surface temperature. 7-day mean T2m anomalies are determined for April 1979–2023 and spatially averaged over the region within the Arctic Circle (north of 66.34°N) where the ARs prevailed for at least three days. The T2m anomaly for the target period is identified within this reference distribution and the percentile is determined.

For precipitation, 7-day accumulated amounts are computed at each grid cell for April 1979–2023. The values for the target period are then compared against the corresponding local reference distributions to determine their percentiles.’ See lines 114-127 on pages 4-5.

Q: The moisture sources for the "Siberian" AR need to be better explained and contextualized. The authors suggest in L410–419 that the 2020 Siberian heat wave provided a significant moisture reservoir for the Siberian AR. However, Fig. 12 shows that the majority of moisture uptake occurred further west over southern and central Europe. Further, the two references cited in L413 do not seem to directly support a Siberian moisture source for this AR – Kwon et al. (2021) is about the impacts of this heat wave on CO2 uptake, while Fig. 3 in Gloege et al. (2021) does show some positive soil moisture anomalies over Siberia, but these appear to be spatially displaced from the area of moisture uptake in Fig. 12 of this paper. Do the authors contend that evapotranspiration from land areas can constitute a significant moisture source for ARs during the spring, and is there support for this in the literature? Or is there some other process in the atmosphere that results in the moisture uptake over Eurasia in Fig. 12? Relatedly, it's not clear to me how the conclusion is reached that "a portion of the moisture reaching the central Arctic is not newly acquired over Eurasia but carried from more distant regions over a period exceeding seven days". Could the authors spell out in more detail how this conclusion follows from the observations in the previous sentences?

A: We thank the reviewer for raising this point. We agree that the conclusions regarding moisture sources and sinks of the Eurasian AR require a clearer explanation. The reviewer is correct in that the primary moisture uptake occurs over central and eastern Europe, spatially coinciding with regions of strong moisture loss. This alignment suggests substantial moisture recycling within the AR, consistent with previous studies. It further implies that much of the moisture is not newly acquired along the AR pathway but was already present in the air parcels transported from lower latitudes.

To better reflect this, we have revised and expanded the discussion which now reads: *'While moisture uptake was most pronounced over central and eastern Europe, a secondary uptake region is evident east of the Ural Mountains over western Siberia. The close spatial alignment between moisture uptake and loss regions suggests that a substantial fraction of moisture is locally recycled within the AR (Nusbaumer and Noone, 2018), indicating that parcels already carried elevated moisture content when being incorporated into the AR airmass and highlighting the role of long-range transport in sustaining AR moisture content. In addition, moisture uptake over western Siberia may reflect land-surface feedbacks. Previous studies have shown that an intense and persistent heat wave affected Siberia in early 2020 (Ciavarella et al., 2021; Overland and Wang, 2021), leading to an unusually early onset of snowmelt and enhanced soil moisture (Gloege et al., 2022) that may have acted as a moisture reservoir for the Eurasian AR.'* See lines 452-460 on page 23.

Q: It appears that rainfall is quantified using ERA5 data in this study (L93). Although the partitioning of rain vs snow is not a central focus of the work, the uncertainties in quantifying precipitation amount and phase using reanalysis data should be acknowledged. For example, L257 states that "a mix of rain and snow is observed" and L267 states that "intermittent rainfall events are measured" - since this is reanalysis data, the text should be clear that rainfall is simulated rather than observed or measured. Can the authors provide any references to show that ERA5 rainfall data are reliable in the Arctic?

A: Following the reviewer's comment, we have added a short discussion in Section 2.1 acknowledging the limitations of ERA5 precipitations in the Arctic. The new text reads: '*ERA5 perform well in the Arctic, capturing the spatial and temporal variability of key variables such as temperature, wind speed, and specific humidity (Graham et al., 2019; Hersbach et al., 2020). Further, ERA5 effectively represents snowfall events at high latitudes and shows good agreement with independent in situ datasets in distinguishing between rainfall and snowfall, although uncertainties remain, particularly over ocean regions where observational data are sparse (Barrett et al., 2020; Cast et al., 2025; Xiong et al., 2022).*' See lines 105-109 on page 4.

We have also revised the sentences noted by the reviewer to avoid implying that precipitation was directly observed:
'*Intermittent and well-defined precipitation events are recorded in SEG with daily totals exceeding 10 mm day^{-1} (Fig. 6c). In early April, rainfall remains low, whereas later a mix of rain and snow occurs. (...) Rainfall in BKS remains generally low (Fig. 6d) due to persistent sub-zero temperatures, although intermittent rainfall events do occur.' See lines 296-308 on pages 13-14.*

Q: Title and abstract: I wonder if it's worth mentioning in the title and abstract that the two ARs being studied took place during the MOSAiC field campaign (i.e. maybe the title could be something like "Impact, drivers, and pathways of two Arctic atmospheric rivers during MOSAiC in April 2020"). Upon first reading the paper, I was a bit confused on why these two ARs in April 2020 were being studied, and the connection to the MOSAiC campaign with its rich observational dataset would make the context and motivation of the study more clear to readers. However, this isn't a strong opinion, and I will leave it to the authors' discretion as to whether they accept this suggestion.
A: We agree with the reviewer that mentioning the MOSAiC field campaign earlier on will strengthen the motivation and reach of this study. We have chosen to include a mention of MOSAiC early in the abstract as follows: '*Here, we adopt a combined Eulerian-Lagrangian framework to investigate two intense ARs that penetrated into the central Arctic within one week in April 2020 during the MOSAiC field campaign. This study provides a comprehensive view of their large-scale dynamics, moisture sources, and thermodynamic evolution.'* See lines 2-5 on page 1.

Q: Fig. 1 and elsewhere: Maybe nitpicking, but I'm not sure if "Siberian" is the best description of the second AR. From Fig. 1 it appears that the AR spent much of its life cycle over central and eastern Europe before entering the Arctic from western Siberia. Perhaps "Eurasian" would be a more accurate label?
A: We agree with the reviewer's remark. As the AR travels over central Europe, Scandinavia, western Siberia and the central Arctic, the term '*Eurasian AR*' seems more appropriate. The name has been changed throughout the manuscript.

Minor specific comments:

Q: L12: The way the abstract reads right now, "one group of parcels" is described without any mention of the other parcel groups. I understand after reading the rest of the paper that this is the group of "AR-like" air parcels that is singled out for more detailed analysis, but it would be helpful to try and make this a little more clear in the abstract. I suggest a rewrite to something like "During both AR events, there is a group of parcels that experiences overall cooling and increases in potential temperature associated with classic AR characteristics: ..."
A: We thank the reviewer for this comment. We have followed the suggestion and changed the abstract, which now reads: '*During both AR events, a subset of air parcels exhibiting classic AR characteristics is identified. These warm, moist, low-pressure airmasses ascended upon arrival and released intense precipitation.*' See lines 13-14 on page 1.

Q: L19: Atmospheric rivers are typically defined according to strong water vapor *transport*, not just enhanced presence of water vapor. See the definition in the American Meteorological Society Glossary of Meteorology: https://glossary.ametsoc.org/wiki/Atmospheric_river
A: We have taken the reviewer's comment into account and changed the term 'water vapor' to 'water vapor transport'. See line 20 on page 1.

Q: L36–46: Another useful reference on the physical mechanisms that induce Arctic warming (in this case, specific to Greenland) associated with AR-like air streams, and analyzed from a Lagrangian perspective, is Hermann et al. (2020).
A: We thank the reviewer for mentioning this reference and cited the paper.

Q: L65: This is a bit of an abrupt transition to discussing the two April 2020 AR events. Some transition language about why these ARs are being studied would be helpful. Maybe the introductory text from the succeeding paragraph could be pulled forward to introduce this case study, i.e. something like "Previous studies have examined a sequence of two strong ARs that impacted Arctic sea ice during the MOSAiC campaign during April 2020..."
A: We acknowledge that the transition into the case study was abrupt. The first sentence introducing the two AR events has been modified to be more appropriate for opening a paragraph. It now reads: '*A remarkable sequence of ARs occurred during 13-21 April 2020, during which two distinct ARs travelled along different pathways before intruding and merging in the central Arctic.*' See lines 75-76 on page 3.

Q: L173: "within a few days"... of what? Within a few days of entering the Arctic, or a few days after their origin as AR features?

A: We thank the reviewer for pointing out this ambiguity. The sentence has been altered to '*Both ARs reach RV Polarstern within a few days of one another.*' See line 198 on page 7.

Q: L184: How are "residual AR airmasses" defined? I do not see anywhere these residual AR airmasses are represented in the figures.

A: With the term 'residual' we were referring to the remaining AR plume that persists in the Arctic for days, lingering close to the North Pole before dissipating. To avoid any confusion, we have decided to delete the word, so that the sentence now reads: '*After the two ARs merge in the central Arctic on 19 April, AR airmasses persist until 21 April, sustained by anomalous low pressure north and north-west of Greenland and by two anticyclones, one over central-eastern Siberia and the other over Scandinavia.*' See lines 209-211 on page 7.

Q: Fig. 3: This figure would be easier to interpret if there were minor ticks on the x-axis at the start of each day. I also suggest locating the major x-axis ticks and labels every 5 days, i.e. at 5 Apr, 10 Apr, etc.

A: We have added minor ticks to the x-axis to improve readability. After careful consideration, we retain major ticks at four-day intervals but shift them to mark 12, 16, and 20 April. Using five-day intervals would result in only two labelled dates on the x-axis, making the figure more difficult to interpret.

Q: L210–211: It looks to me like the spike in precipitation is simultaneous, or even slightly leads, the peak in Q2m...?

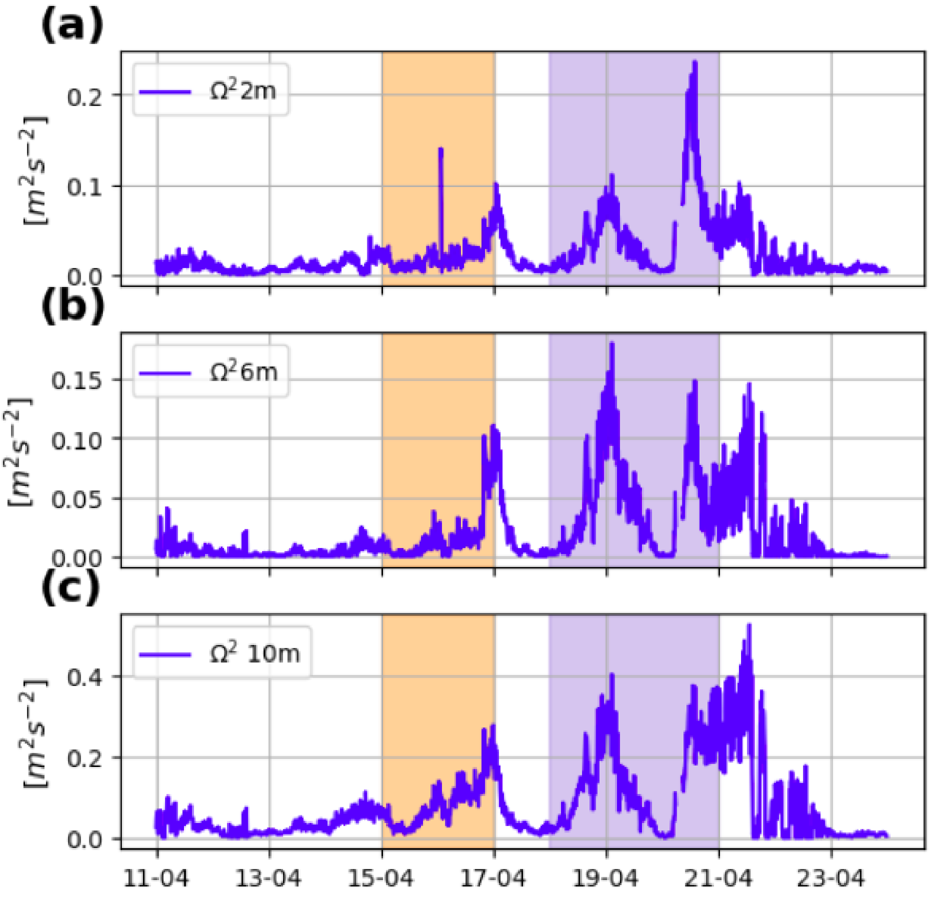
A: This inconsistency has been noted by reviewer #2 as well and corrected in the text. The altered passage now reads: '*A spike in total precipitation occurs while the Eurasian AR remains above the ship on 16 April (Fig. 3e), followed by a sharp decline in Q2m due to the removal of atmospheric moisture through precipitation, and accompanied by a marked decrease in SEB.*' See lines 241-243 on page 11.

Q: L218: From Fig. 3b, it looks like the peak in precipitation is more like 1.5 times greater for the second AR? (not 2.5 times)

A: We thank the reviewer for reading the manuscript so carefully. We have changed the incorrect '2.5' to the correct '1.5'; see line 250 on page 11.

Q: L220–221: I agree that turbulent fluxes appear to contribute only marginally during the positive-SEB part of the second AR event, although it is a bit hard to say for sure because of the different shapes of panels (d) and (e) in Fig. 3 and because of the missing SEB data for part of the event in Fig. 3d. But what about the strong positive SHF during the latter stages of this event? Do the authors have any hypothesis or explanation about what causes this (multi-day?) spike in SHF?

A: Following a comment by referee #3, we have added a panel to Fig. 3 showing the 10-m wind speed (WS10m) at RV Polarstern and, thus, changed the layout of the figure so that all panels are of the same shape, making them more comparable. The increase in SHF towards the latter part of the Atlantic AR period is likely caused by a larger surface-to-air temperature gradient (Tsurf – Tair), stronger wind speeds, or a combination of both. Before this point, SHF and wind speed are not correlated. Because the increase in SHF follows an intense precipitation event, it might also be linked to increased turbulence or reduced atmospheric stability. This is consistent with higher Ω^2 values (squared vertical velocity) observed during the same period, i.e., the latter part of the Atlantic AR event (see figure below). We now have added the following sentence to the manuscript: '*From 20 April, sensible heat flux increases over a two-day period, due to an enhanced surface-to-air temperature gradient, increased wind speeds, or a combination of both*.' See lines 254-255 on page 11.



Q: Fig. 4: Why is the color scale for the T2m anomaly map (panel a) not centered on 0C?

A: Thank you for noticing this. We have modified the colour bar to be centred around zero.

Q: Fig. 5: The precipitation percentile color scale seems somewhat odd. The linearly increasing color scale does not match the somewhat arbitrarily chosen percentile levels. I suggest finding a color scale to more effectively display this map data.
A: In this panel, we apply a non-linear colour normalisation (matplotlib's TwoSlopeNorm) centred at the 90th percentile to emphasise high-percentile precipitation values, which are the focus of the subsequent Lagrangian trajectory analysis. This approach enhances visual contrast in the upper tail of the distribution, while compressing lower percentile values that are of less relevance here. To clarify this in the manuscript, we have updated the figure caption to read: '*A non-linear normalisation centred on the 90th percentile is used to highlight regions of extreme precipitation.*'

Q: L265: It appears to me (from Fig. 6b) that the temperature over the BKS doesn't actually reach 0C by 18 April, more like -1C or -2C?
A: Thank you for pointing this out. We have corrected the text which now reads: 'T*2m, in contrast, exhibits a sharp increase from -10°C on 12 April, prior to the AR arrival, to values just below 0° C by 18 April.*' See lines 305-306 on page 14.

Q: L267–268, Fig. 6: "During the ARs, precipitation increases substantially" - it appears to me that the increase in precipitation over BKS occurs after the gray-shaded AR period in Fig. 6d?
A: We thank the reviewer for noticing this. The text passage has been corrected and now reads: '*Following the AR retreat, precipitation increases substantially.*' See lines 308-309 on page 14.

Q: L268–270: It's not quite clear to me from Fig. 6 how there is a strong correlation between SIC and rainfall & T2m. Are these correlations calculated at the daily scale, such that the change in SIC is correlated with the daily rainfall and temperature? Could the authors provide more details about how these correlations are calculated?
A: Correlations between T2m, SIC, rainfall and precipitation are computed by calculating the Pearson correlation coefficient for daily time series of the variables pairwise. This has been added to the figure caption to make the process clearer to the readers as follow: '*The Pearson correlation coefficient between the two time series is shown in the panel title.*'

Q: L322–323: How are the air parcels along these "pT..." trajectories interacting with the surface if they are mostly at pressures < 650 hPa (and not located over elevated

terrain)? Is there some other process in the free troposphere that can explain the specific humidity changes in these parcels?
A: We have changed the text to now read: '*Along their trajectories, the temperature and specific humidity increase.*' See line 364 on page 17.

Q: L326–327: I like the decision to focus on a subset of "AR" air parcels chosen using simple physical criteria, rather than all air parcels as a composite. This is an interesting and effective methodological choice.
A: Thank you - this is great to hear.

Q: L339–341: Is there anything that can be concluded from the fact that the percentage breakdown of the air parcel grouping is so different for the Arctic AR comparing to the Greenland-landfalling AR?
A: We thank the reviewer for this remark. The change in percentage of the nTpθ for the Greenland-reaching parcels compared to the central Arctic has been noted by us when preparing the manuscript. This discrepancy could reflect a reduction in strength of the ARs. As we base our trajectory analysis on parcels with endpoints within a confined region in the central Arctic, many nTpθ parcels may have been "lost" along the way. Consequently, when examining the entire air column over the target region, a smaller proportion of parcels exhibit nTpθ characteristics. A brief explanation has been added to the text which reads: '*This difference may reflect the generally weaker strength of the ARs when reaching the central Arctic, reducing the fraction of nTpθ parcels that retain typical AR characteristics.*' See lines 382-383 on page 17.

Q: L343–344: It's really neat to see the distinct pathways of the two ARs in the trajectory density map!
A: Thank you!

Q: L434–435: The Komatsu et al. (2018) paper cited here does not show that Siberian ARs are becoming more frequently occurring features of the Arctic climate system. The only mention of increasing trends in this paper are references to other papers that have analyzed trends in water vapor and precipitation over the Arctic and Eurasia.
A: Thank you for pointing this out. We have decided to modify the sentence to a more general statement about ARs in the Arctic and corrected the citation. The sentence now reads: '*Recent studies show that ARs are becoming more frequently occurring features of the Arctic climate system (Wang et al., 2024; Woods and Caballero, 2016; Zhang et al., 2023), raising important questions about how the combined transport of heat, moisture, and aerosols influences Arctic amplification and cloud radiative forcing.*' See lines 476-478 on page 24.

Technical corrections

Q: L14: Suggest commas around "however"
A: Done.

Q: L70: The word "the" is duplicated in this sentence
A: Thank you for pointing this out. The duplicated word has been removed.

Q: L71: "from ship" --> "from the ship"
A: Fixed.

Q: L80 and Fig. 2 caption: Find a more grammatically appropriate description than "extremeness", such as "extreme nature" or "statistical context"
A: We have changed the term 'extremeness' to 'extreme nature' in the text. It now reads: '*Moreover, key questions remain regarding how unusual the synoptic-scale drivers were that contributed to the extreme nature of the two ARs, how the ARs are linked to surface impacts and sea ice loss beyond the immediate MOSAiC site, and how they evolved thermodynamically along their pathways.*' See lines 91-93 on page 4. The caption of Fig. 2 now reads: '*Assessing the extreme nature of the synoptic weather systems driving the Atlantic and Eurasian ARs based on ERA5.*'

Q: L142: "its life cycle" --> "their life cycles"
A: Done

Q: L157: "5a" --> "Fig. 5a"
A: Done.

Q: L177–178: "along the Atlantic Ocean" is awkward phrasing, please rephrase
A: We have rephrased the sentence which now reads '*The second AR, the Atlantic AR, propagates northward over the Atlantic Ocean and reaches the Arctic Circle three days after the Eurasian AR on 16 April.*' See lines 202-203 on page 7.

Q: L226: "After having" --> "Having"
A: Fixed.

Q: Fig. 5 caption: The word "gridded" is unnecessary (it is assumed that ERA5 reanalysis data are on a regular lat/lon grid)
A: The word 'gridded' has been removed from the figure caption.

References

- Hermann, M., Papritz, L., & Wernli, H. (2020). A Lagrangian analysis of the dynamical

and thermodynamic drivers of Greenland melt events during 1979–2017. _Weather and Climate Dynamics_, _1_(2), 497–518. https://doi.org/10.5194/wcd-1-497-2020
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