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 428).

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 boxes120 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 455-462 on page 24.

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.

<u>Minor specific comments:</u>

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.

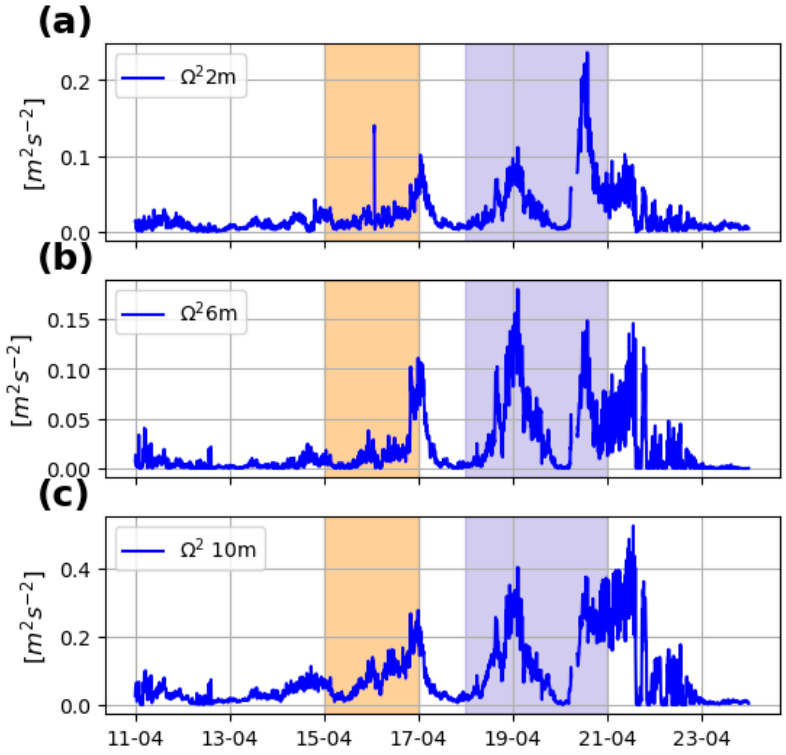
Q: Fig. 3: This figure would be easier to interpret if there were minor ticks on the x-axis at the start of each day. I also suggest locating the major x-axis ticks and labels every 5 days, i.e. at 5 Apr, 10 Apr, etc.
A: We have added minor ticks to the x-axis to improve readability. After careful consideration, 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: '*T2m, 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 19.

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 478-480 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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