

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 quantitatively 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.

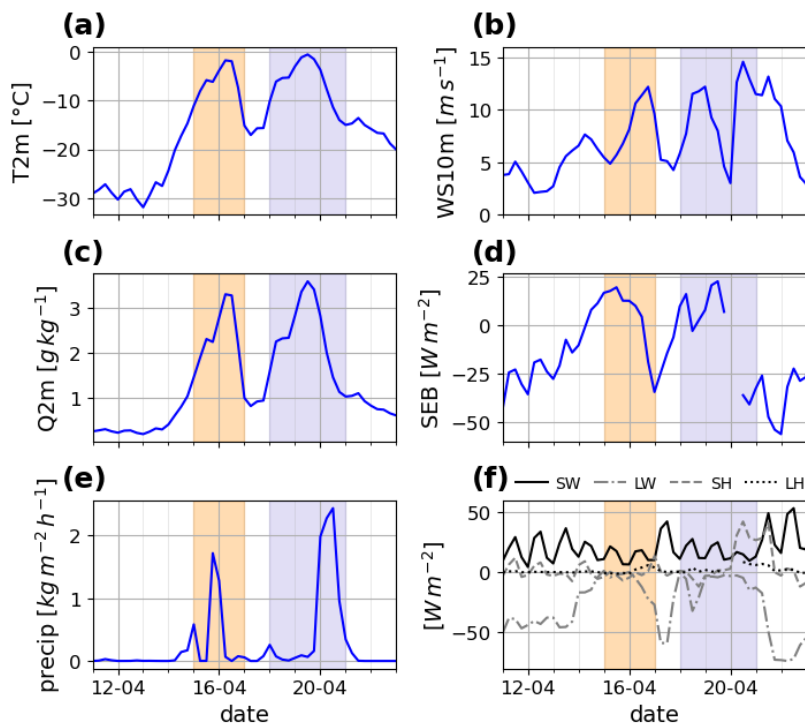
Specific remarks:

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.

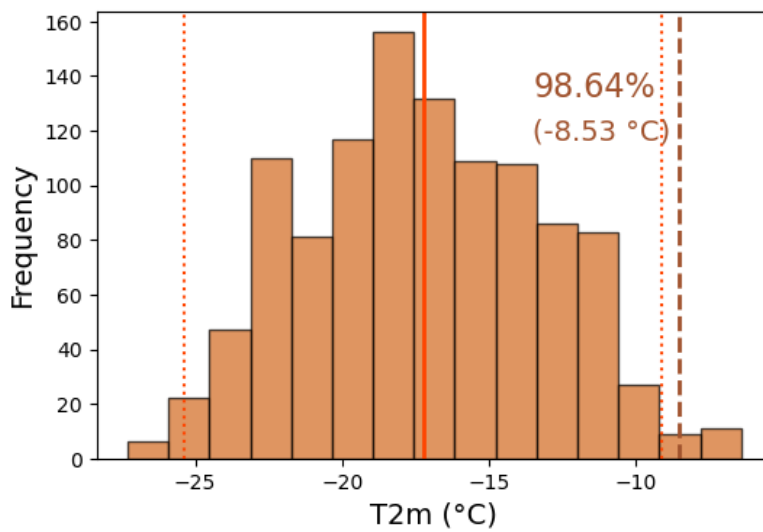
We have added a clarifying sentence at the start of the paragraph that now reads: *‘To assess how unusual the atmospheric conditions associated with the Arctic ARs were, we determine anomalies and accumulated values during the target period against reference distributions constructed using a 7-day moving 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 -13.6°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 ($-13.6\text{ }^{\circ}\text{C}$) (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 comment. 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 6.

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