RC2: 'Comment on egusphere-2026-2066', Anonymous Referee #2, 19 Jun 2026

The study by Bailey et al. presents a well-structured case study of an extreme atmospheric river (AR) event that affected Svalbard in mid-March 2022, followed by a cold air outbreak (CAO) at the end of March. The authors analyse the AR event using isotope measurements, radiosonde data, and meteorological observations from Svalbard, supported by reanalysis data. First, the manuscript provides an overview of the event in a climatological context, then examines the vertical structure of the AR, and finally discusses surface-based analysis in detail. Overall, this is an interesting and relevant case study that illustrates the impact of atmospheric rivers and related extreme events on polar regions. The results are clearly presented and provide a good overview of the key parameters associated with ARs.

Overall, I think, the manuscript is well written and addresses an important topic and is suitable for publication after addressing some specific concerns.

Thank you for the positive and constructive review. We appreciate the helpful suggestions which will improve the clarity of the Methods, figures, and Discussion. In a revised manuscript, we will address each of the specific comments below in detail, including clearer motivation for the isotope and aerosol measurements, expanded treatment of the CAO and its relationship to the AR, and additional clarification of the reanalysis products and figure presentation.

Specific comments:

1) Unlike the AR analysis, the COA analysis is comparatively limited and would benefit from a more detailed discussion, given its relevance to the evolution of the overall event. I think it would be interesting to include a comparison between the AR and the CAO. For example, to what extent was the CAO anomalous (or not) compared to typical Arctic cold air outbreaks? Is there any indication that the AR may have influenced or triggered the CAO?

Thank you for this helpful suggestion. We agree that the CAO deserves more detailed treatment and a clearer comparison with the preceding AR. In a revised manuscript, we will add a new supplementary figure showing ERA5 daily mean sea-level pressure evolution from 14-21 March 2022, together with cyclone back-tracking from the CAO-associated low near Svalbard on 21 March (Fig. S3). This new analysis indicates that the CAO was dynamically linked to the AR through the evolution of the same synoptic-scale cyclone system, rather than being an unrelated event.

We will add the following to the Methods:

"To examine the synoptic evolution linking the AR and subsequent CAO, the progression of the associated cyclone was tracked using ERA5 hourly sea-level pressure fields sampled at 6 h intervals. The track was initialised from the CAO-associated SLP minimum near Svalbard on 21 March 2022 and reconstructed backward in time by identifying the nearest constrained SLP minimum at each preceding 6 h timestep. The resulting track was compared with ERA5 daily mean SLP fields from 14–21 March 2022."

We will rename Section 3.1 "*Atlantic bomb cyclogenesis and AR–CAO evolution*" and add the following to the Results:

"Cyclone back-tracking shows north-eastward progression of the system through the Greenland Sea-Fram Strait sector toward Svalbard and the northern Barents Sea over the subsequent four days (Fig. S3). By 21 March, this migration had reorganised the pressure field around Svalbard, shifting the flow from warm, moist south-westerly advection during the AR to northerly/northeasterly cold-air advection during the CAO."

We will also strengthen the AR-CAO comparison in the Discussion:

"The subsequent CAO provides the contrasting isotopic end-member of this coupled AR–CAO sequence (Fig. S3). As the cyclone migrated north-eastward, south-westerly advection was replaced by cold northeasterly flow. This produced depleted vapour isotopes with a shallower $\delta^{18}O$-$\delta^{2}H$ slope, consistent with stronger kinetic fractionation during air-mass transformation across the sea ice-open water boundary in the Fram Strait under cold, lower-humidity conditions (Brunello et al., 2023; Mix et al., 2019). Na^+ also returned to near-background concentrations (~0–0.1 µg m^{-3}), indicating replacement of the Atlantic marine aerosol plume by a distinct Arctic air mass. The low Na^+ values are consistent with transport over more sea-ice-covered regions and reduced open-ocean marine boundary-layer influence, limiting sea-salt aerosol entrainment during the CAO."

To provide local context for how anomalous the CAO was, we will also clarify that IWV dropped below 1.2 kg m^{-2} during the CAO, below the 3rd percentile of March values in the 1993-2022 Ny-Ålesund radiosonde record.

2) The manuscript includes isotope measurements, which are a potentially interesting component of the study. However, the motivation for including them and their specific added value could be clarified. In particular, it would be helpful to explain more clearly what additional information they provide beyond the meteorological analysis, for example with regard to moisture source regions or transport pathways.

Thank you for this helpful comment. In a revised manuscript, we will clarify that the isotope and aerosol measurements provide process-level information that complements the meteorological analysis. While the ERA5 synoptic fields indicate the transport pathway, the vapour isotope and Na^+ aerosol measurements provide evidence for the character and history of the transported air mass: enriched $\delta^{18}O$, negative d-excess, a near-meteoric slope, high humidity and enhanced marine Na^+ collectively support rapid poleward transport of Atlantic marine moisture with limited progressive rainout and limited wet scavenging along the AR pathway.

We will revise Section 4.1 as follows:

"Our vapour isotope record captures distinct pulses of Atlantic moisture marked by elevated $\delta^{18}O$, negative d-excess, and a near-meteoric slope, indicating high-humidity marine evaporation and – crucially – limited progressive rainout during the poleward transport (Bailey et al., 2021; Bonne et al., 2015; Leroy-Dos Santos et al., 2020). The concurrent spike in marine Na^+ aerosol further supports sea-salt entrainment from marine boundary-layer sources along the North Atlantic-Greenland Sea AR corridor (Figs. 1 and 2), consistent with direct Atlantic influence and limited upstream wet scavenging of sea-salt aerosols during transport (Yamagata et al., 2009)."

We will also add a brief archive/paleoclimate implication to our Discussion:

"Because the March 2022 AR occurred in winter, its enriched isotope signal stands out against a depleted cold-season baseline; comparable summer AR signals may be harder to distinguish from the seasonal isotope maximum. AR-related winter $\delta^{18}O$ enrichment has similarly been observed in the firn record at a cold, high-elevation site with limited melt influence on the Greenland Ice Sheet (Bailey and Hubbard, 2025), demonstrating that such events can be preserved under favourable conditions. In Svalbard, however, meltwater percolation can modify firn $\delta^{18}O$ signals and may also redistribute soluble aerosol species, complicating preservation in lower-elevation glacier and ice-field records (Spolaor et al., 2024). Where preserved, enriched isotope layers accompanied by marine aerosol markers such as Na^+ may therefore archive extreme marine moisture transport and AR landfalls, rather than simply recording local palaeotemperature."

Spolaor, A., Scoto, F., Larose, C., Barbaro, E., Burgay, F., Bjorkman, M.P., Cappelletti, D., Dallo, F., De Blasi, F., Divine, D. and Dreossi, G., 2024. Climate change is rapidly deteriorating the climatic signal in Svalbard glaciers. *The Cryosphere*, *18*(1), pp.307-320.

3) The discussion is sufficient, however, I suggest dividing it into several subsections to improve readability and provide a better overview. For examples:

-Precipitation characteristics and isotopic evidence

- Poleward moisture transport and AR structure A

- Atmospheric thermodynamic response and SEB

- Cryospheric response (melt, refreezing, snowpack)

Thank you for this helpful suggestion. In a revised manuscript we will divide the Discussion into the following sub-sections:

Moisture transport and geochemical evidence

Surface energy balance and cryospheric response

Minor comments

L22, L88, L96: The measurement campaign is mentioned several times throughout the manuscript. It would be helpful to provide a brief introduction to the campaign, including its location and duration. If I understand correctly, the measurements were conducted at the NPI Zeppelin Observatory between 1 January and 31 May. Please clarify.

Yes, and in a revised manuscript we will clarify that the campaign was conducted at the NPI Zeppelin Observatory, Ny-Ålesund, from 1 January to 31 May 2022, and that it included continuous water vapour isotope and humidity measurements, with concurrent aerosol measurements used to assess Na^+ during the event.

L76: I would like to clarify one point regarding the measurements. Are the stable isotope ratios derived from the measured water vapour isotope ratios? Also, is the temporal resolution approximately one second?

Yes, and we will clarify this in a revised manuscript. The stable isotope ratios, expressed as $\delta^{18}O$ and $\delta^{2}H$ in the text, are derived from the measured water vapour isotopes $^{18}O/^{16}O$ and $^{2}H/^{1}H$. The raw instrument measurement was approximately one second (as stated on L84), but the data were averaged to 5 minute averages for analysis and plotting (L92).

L96: Could you explain the motivation for using snowfall samples and explain their relevance to this study?

The snowfall samples provide an event-scale precipitation isotope constraint that links the continuous vapour isotope measurements to the deposited snowpack. In the Results, we show that snowfall $\delta^{18}O$ and d-excess broadly track the vapour variability but are systematically enriched relative to vapour by ~11 ‰, consistent with expected vapour-to-condensate equilibrium fractionation. This offset is useful because it indicates that the AR vapour isotope anomaly was transferred into snowfall in a physically consistent way, and also supporting the interpretation that such events may leave a detectable signal in snow/firn archives. In a revised manuscript we will clarify the motivation for including the snowfall isotope samples:

We will keep the Results statement observational:

"Snowfall isotope samples from Ny-Ålesund broadly track the water vapour variability, but are systematically enriched relative to vapour by ~11 ‰, consistent with vapour-to-condensate fractionation (Supplementary Table S1)."

We will then add the archive implication to the Discussion:

"Because the March 2022 AR occurred in winter, its enriched isotope signal stands out against a depleted cold-season baseline; comparable summer AR signals may be harder to distinguish from the seasonal isotope maximum. Moreover, the systematic offset we observe between vapour and snowfall isotopes is in line with vapour-to-condensate fractionation, suggesting that the AR isotope anomaly was transferred into deposited snow and may therefore be captured by the snowpack/firn record."

L126ff: The study uses both ERA5 and CARRA reanalysis data. What are their respective temporal and spatial resolutions? References for both datasets should also be provided. Currently, Hersbach et al. (2020) is cited repeatedly throughout the manuscript instead – it should be sufficient to cite it once.

In a revised manuscript, we will clarify the temporal and spatial resolutions of both reanalysis products in the Methods (hourly to daily, and ~2.5 km and 31 km, respectively), and cite each dataset there rather than repeatedly throughout the Results.

L136 and Figure 1: Could the transect be added to Figure 1? This would help the reader to identify its location and better follow the subsequent analysis more easily.

Thank you for this suggestion. We agree that the transect location should be easier to identify. Because the transect is not mentioned or used until the Figure 3 cross-section analysis, we will incorporate the transect locator map into Figure 3a and clarify the transect coordinates in the Methods, so that it is clearly introduced at the point where it is used and first appears in the manuscript.

L176: Delete the citation Hersbach et al. (2020).

We will delete this repeated citation.

Figure 2: It would be informative to also show anomalies for IVT and precipitation to illustrate more clearly how exceptional this event was. In addition, I suggest using the same latitudinal range for all three panels to facilitate comparison.

Thank you for this suggestion. We agree that using a consistent latitudinal range will make Figure 2 easier to compare across panels, and we will revise the figure accordingly. However, we prefer to retain absolute IVT and precipitation values in the main figure rather than replacing them with anomalies. For IVT, the absolute magnitude is important for identifying and classifying the AR itself, including the >450 kg m^{-1} s^{-1} transport corridor. Similarly, absolute precipitation totals are directly relevant to the event impacts and allow the reader to assess the magnitude of precipitation delivered to Svalbard and surrounding regions (e.g., SE Greenland). To make the exceptional nature of the event clearer, we will strengthen the accompanying text/caption to describe the anomalous character of the IVT and precipitation fields, while preserving the absolute values in the figure.

L180ff: Please clarify how turbulence was diagnosed or calculated. Could you indicate where the negative potential vorticity mentioned in the text can be found?

Thank you for pointing this out, we agree that the original wording was ambiguous. The turbulence shown in the cross-section is not diagnosed independently from observations, but is the model-derived turbulence diagnostic from CARRA, whose core atmospheric model is HARMONIE-AROME. In a revised manuscript, we will clarify this in the Methods/figure caption, as well as the reference to negative potential vorticity; if this is not shown explicitly in the revised figure, we will remove the statement from the text.

Figure 3: I suggest incorporating the inset map shown from panel (c) already into panel (a). Furthermore, the cross section in Figure 3 is shown at 12 UTC, whereas Figure 2 shows conditions at 16 UTC. To improve consistency, I suggest using the same time step for both figures.

Thank you for this suggestion, we will do as suggested. The 12 UTC label in Figure 3 was an error; in a revised manuscript, we will correct the Figure 3 caption/label to 16 UTC.

L192–193: How was the horizontal wavelength determined? What evidence supports the interpretation that the observed structure is consistent with orographically forced gravity waves?

In a revised manuscript we will clarify that the ~10-50 km horizontal wavelength was estimated graphically from the spacing of repeated wave-like perturbations along the CARRA cross-section. These perturbations are expressed as vertically oscillating moisture and isentropic structures downstream of the steep NW Svalbard topography, which is consistent with terrain-induced/orographic gravity-wave activity.

L212: Figure 3e does not appear to be present. Please check the figure reference.

Thank you – this will be changed to Figure 3c.

L215: Could you provide some context on whether the IWV values observed during this event were exceptionally high compared to climatological conditions?

Yes, this context is already given on L221 where we state that AR IWV peaked at 14.6 kg m^{-2}, the highest March value in the 1993–2022 Ny-Ålesund radiosonde record (Maturilli, 2022).

L220: Please specify which anomalies are referred to here. Alternatively, do you mean temporal variability?

We agree that "anomalies" was ambiguous here. We were referring to the strongest event-scale thermodynamic and moisture departures during the AR, rather than formally calculated climatological anomalies. In a revised manuscript, we will rephrase this sentence to avoid ambiguity:

""The AR intensified on 15 March, producing the strongest thermodynamic and moisture perturbations of the event (Fig. 4)."

Figure 5: Please clarify whether the plotted values are daily means. Is there a particular reason for showing the time series from January to May? Since the focus is on the event in March, a shorter period similar to that shown in Figure 4 might be sufficient.

We will clarify in the Figure 5 caption whether the plotted values are daily means or higher-frequency observations.

We present the full 1 January to 31 May 2022 time series because it provides important context for identifying the March AR and subsequent CAO, and for showing how abrupt the associated meteorological, isotope and aerosol perturbations were relative to background winter-spring conditions. These departures would be less clear in a March-only time window, whereas Figure 4 already provides the shorter event-scale view.

L275: Delete the citation Hersbach et al. (2020).

Done.

L288, L292: Delete the citation Hersbach et al. (2020).

Done.

Figure 7: Could you assess whether the displayed anomalies are statistically significant?

Thank you for this suggestion. Yes, the statistical significance of the displayed anomalies could be assessed relative to the March 1981–2010 reference period and shown using hatching to identify regions where anomalies exceed interannual variability. In its present form, Figure 7 shows anomalies for six variables relative to the March 1981–2010 baseline, with the aim of highlighting the spatial pattern and physical co-occurrence of the event anomalies rather than presenting a gridpoint-by-gridpoint significance test. Because adding hatching to all six panels may obscure these spatial relationships and reduce readability, we will first assess whether such an overlay remains visually clear. If so, we will indicate regions where anomalies exceed interannual variability; if not, we will clarify the anomaly reference period and relative anomaly magnitude in the caption/text.

Figure 7: Delete the citation Hersbach et al. (2020) from the figure. Instead, indicate in the caption that the data are based on ERA5.

Done.

L320: Consider rephrasing to ‚during poleward transport' to ‚during the poleward transport'

Done.

L321: Could you please elaborate on the implications of this result? Why is this finding important?

In a revised manuscript, we will clarify that the Na^+ spike is important because it provides aerosol-based evidence for sea-salt entrainment from Atlantic marine boundary-layer sources along the AR pathway. When interpreted together with enriched vapour isotopes, negative d-excess and high humidity, the Na^+ signal indicates that the AR retained a coherent Atlantic marine isotope–aerosol signature during poleward transport, with limited rainout and wet scavenging before reaching Svalbard. Thus, the aerosol measurements provide source and transport-pathway information that complements the meteorological analysis, rather than simply documenting an additional variable.

We will revise the sentence as follows:

“The concurrent spike in marine Na^+ aerosol further supports sea-salt entrainment from marine boundary-layer sources along the North Atlantic–Greenland Sea AR corridor (Figs. 1 and 2), consistent with direct Atlantic influence and limited upstream wet scavenging of sea-salt aerosols during transport (Yamagata et al., 2009). Together with the enriched vapour isotope composition and negative d-excess, this indicates that the AR retained a strong Atlantic marine signature during poleward transport.”