Reply to RC1: 'Comment on egusphere-2026-2066', Jonathan Wille, 18 Jun 2026

General comments

This study presents a detailed case study of an extreme atmospheric river (AR) event and subsequent cold air outbreak (CAO) that affected Svalbard in March 2022. Combining detailed analysis of the synoptic meteorology, glaciological impacts, surface conditions, and aerosol/moisture transport, the authors have made a holistic analysis using high-quality measurements to present to the reader the many different components of extreme weather events in polar regions. The authors demonstrate a good command of the existing literature and frame this event as a detailed example of how further extreme weather events will impact the Arctic glaciers and ice sheets. The results are robust and paint a complete picture of this extreme weather event from the dynamics to the glacier impacts. The discussion is sufficient, but would benefit of greater detail and further elaboration. Some suggestions are outlined in my Specific comments below.

Overall, I feel this manuscript is well written and the analysis is robust and timely. I would support publication after the following concerns are addressed.

Thank you for your positive and constructive assessment of the manuscript. In a revised manuscript, we will address all of the points and suggestions raised in your review, including the detailed line-by-line comments, figure revisions, methodological clarifications, and citation corrections. We will also strengthen the Discussion by: (i) comparing the March 2022 Svalbard AR with Antarctic AR landfalls; (ii) expanding the interpretation of the subsequent CAO and its relationship to the AR; and (iii) developing the isotope and aerosol observations as process-level evidence for the moisture pathway and potential snow/firn archive imprint.

Specific comments

1. It could be valuable to include a comparison of Antarctic and Arctic AR behavior in the Discussion section. Particularly, the radiosonde measurements during AR landfalls discussed in Gorodetskaya et al. (2020) and Antarctic AR dynamics discussed in (Terpstra et al. 2021) are potentially interesting to compare against the results in this study. Also would be interesting to know if you observed a similar lifting/weakening of the low level jet as the AR moves poleward and over colder ocean waters as is often observed around Antarctica. A similar comparison could also be made with Antarctic water vapor isotope measurements during ARs (see Dutrievoz et al. 2026).

We agree that a brief comparison with Antarctic AR landfalls provides useful context. Notably, we do not observe the same clear vertical decoupling between the humidity maximum and low-level jet described for some Antarctic coastal ARs (e.g. Gorodetskaya et al. 2020). In a revised manuscript we will edit the Discussion to include this comparison:

"This lower-tropospheric moisture-wind structure is comparable to radiosonde-observed Antarctic AR landfalls, where specific humidity reaches ~4 g kg^{-1} and strong low-level jets drive enhanced moisture transport (Gorodetskaya et al., 2020). Yet in contrast to Antarctic coastal ARs where humidity maxima and low-level jets may be vertically decoupled, the Svalbard AR showed a more vertically coherent lower-tropospheric moisture-wind anomaly that was primarily modified by NW Svalbard's steep topography at landfall, producing uplift, local flow variability, turbulence, and lee-side cloud/moisture depletion (Fig. 3). Together, these observations indicate that the March 2022 AR delivered a moisture-rich Atlantic air mass to Svalbard with minimal depletion during transport, maintaining high atmospheric humidity and priming the surface for strong radiative forcing."

2. There is only one brief mention of the cold air outbreak (CAO) in the Discussion section. It is very interesting that this very intense AR was followed by an exceptionally intense CAO shortly afterwards, but there is no discussion as to whether these two events are related. Is it possible to examine your datasets and determine how often intense ARs are followed by CAOs?

We agree the CAO deserves more detailed discussion. In a revised manuscript, we will include a new supplementary analysis 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. This analysis indicates that the CAO was dynamically linked to the AR through the evolution of the same synoptic-scale cyclone system.

Although a climatological frequency analysis of how often intense ARs are followed by CAOs would be a valuable direction for future work, we will not add this here because it would require developing new and consistent Arctic/Svalbard-specific AR and CAO catalogues, which lies beyond the scope of the present event case study.

We will revise the manuscript as follows:

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."

Results: We will rename section 3.1 "*Atlantic bomb cyclogenesis and AR-CAO evolution*", and add the following:

"Cyclone back-tracking shows north-eastward progression of the system through the Greenland Sea-Fram Strait toward Svalbard and the northern Barents Sea over the subsequent four days (Fig. S?). 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/north-easterly cold air advection during the CAO."

Discussion: We will add the following interpretation to Section 4.1:

"The subsequent CAO provides the contrasting isotopic end-member of this coupled AR–CAO sequence. As the cyclone migrated north-eastward, south-westerly advection was replaced by cold north-easterly 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."

3. The isotope and aerosol measurements are certainly interesting details, but I feel they exist in this study only as a detail. For instance, the concluding sentence at the end of the second paragraph in the discussion summarizes something that has already been observed many times before in previous Arctic AR events. Perhaps there is potential to use these results to support larger conclusions that can

be mentioned in the Discussion section. Like do the aerosol and isotope measurements reveal anything about the source region of the moisture, something that is different from a regular cyclone event? Do the enhanced isotopes from this event have any paleoclimate significance? Like is this signal something to can be found in the ice core records of other extreme weather events. I am not suggesting making additional analysis although a moisture tagging analysis would be a good way to determine the origin of the moisture, but try diving a bit deeper to make further connections with other events and hypothesize the implications of these results.

Thank you for this helpful suggestion. In a revised manuscript we will place the isotope and aerosol measurements in a broader source-region and archive context. Specifically, we will add the following text 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. AR-related winter $\delta^{18}O$ enrichment has similarly been observed in the firn record at a cold, high-elevation site on the Greenland ice sheet (Bailey and Hubbard, 2025), demonstrating that such events can be preserved under favourable conditions (i.e., limited melt). 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 paleotemperature.”

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.

Minor comments

Line 39-42: Mostly because of the timing, but it would be nice to mention the extreme Antarctic AR event in March 2022 as a co-occurring polar extreme on the other side of the planet (Wille et al. 2024a,b).

We will add these citations in the Introduction to acknowledge the Antarctic AR event, and mention in a revised Discussion that the Svalbard AR coincided with the extraordinary East Antarctic AR:

“Notably, this event occurred in the same month as an extraordinary AR-driven heatwave in East Antarctica (Wille et al., 2024a, b), highlighting the capacity of meridional moisture transport to generate polar extremes in both hemispheres.”

Line 108: Mention the years of the radiosonde record in the Methods.

We will add that the event-context statistics are calculated relative to the March radiosonde record from 1993–2022.

Line 140: Please specify the resolution difference between CARRA and ERA5.

We will specify that CARRA has substantially higher horizontal resolution than ERA5, with grid spacing of ~2.5 km compared with ~31 km for ERA5.

Line 181: Is there a figure that shows the potential vorticity? If not, you can just write "(not shown)".

We will add this.

Line 195: Did you find a foehn wind within the lee-side flow?

We examined the CARRA cross-section for evidence of foehn flow. The section shows strong orographic modification of the AR as it crossed NW Svalbard, including uplift over the terrain and a sharp reduction in cloud liquid water downstream of Holtedahlfonna, consistent with lee-side moisture depletion. However, we do not identify a clear lee-side warming signal in the temperature field, and we therefore do not diagnose a classic foehn event.

Line 228: "collapsed" is not a very physically descriptive term. Perhaps "dissipated"?

We will change to dissipated.

Line 228: Can you state what quantile the IWV was within?

Yes - the 24 March IWV value of 1.2 kg m^{-2} lies below the 0.03 quantile, i.e., below the 3rd percentile, of all March IWV values in the 1993–2022 Ny-Ålesund radiosonde record. We will add this detail to a revised manuscript.

Line 264: I think it is worth mentioning here that the snow depth actually exceeded the pre-AR levels once the storm passed. Although the snow depth then decreases quickly around March 21st even though the temperatures remained below freezing. Any idea on what caused this?

Thank you for highlight this. We will revise the text to indicate that snow depth increased above pre-AR levels following the post-AR snowfall, but then decreased rapidly around 21 March despite sub-freezing air temperatures. Inspection of the local Ny-Ålesund wind-speed record shows a concurrent increase in both 2 m and 10 m wind speed to approximately 16 m s^{-1} on 21 March. We therefore interpret the snow-depth decrease primarily as a local wind-redistribution/scouring signal, likely aided by post-storm settling or compaction of the fresh snowpack, rather than melt. We will add these details to the manuscript.

Line 320: Rephrase to "during the poleward moisture transport".

We will rephrase this as suggested.

Line 321: Do you have any insight on the source region of the enhanced Na+ aerosol in reference to the trajectory of the AR?

The enhanced Na^+ aerosol signal is interpreted as evidence of a marine sea-salt source associated with the AR pathway, rather than as an independent tracer of a precisely defined source region. The Na^+ enhancement coincided with enriched vapour ^{18}O and ^{2}H, low d-excess, and south-westerly AR transport in the synoptic fields from the North Atlantic/Greenland Sea sector. Taken together, these lines of evidence support a North Atlantic marine origin for the air mass and indicate that sea-salt aerosols were likely entrained from open-ocean marine boundary-layer sources along the AR corridor. We will revise the discussion to make this interpretation clearer.

Line 359: After taking into account the short-term increase in surface mass balance and then the enhanced melting potential from the ice layer formation and firn densification, can you make an educated guess as to whether this AR was a net positive or negative for the long-term surface mass balance?

For the 2022 balance year, the AR was likely a net positive SMB event: snowfall exceeded contemporaneous melt, and independent snow-pit observations showed increased SWE during/after the event, indicating that rainfall was retained within the snowpack rather than immediately lost as runoff. However, this positive annual contribution does not necessarily imply an unambiguously beneficial longer-term effect, as rainfall retention, refreezing, ice-layer formation, and firn densification may reduce pore space and permeability, potentially lowering future meltwater retention capacity. Quantifying this longer-term sign would require coupled surface-energy-balance and firn modelling, constrained by multiple snow-pit observations including SWE, density, and stratigraphy, comparing simulations with and without the AR forcing through the subsequent melt season. This is beyond the scope of the present study, but the available evidence indicates that the AR likely increased 2022 SMB while potentially reducing future firn storage capacity.

References:

Dutrievoz, N., and Coauthors, 2026: Water vapour isotope anomalies during an atmospheric river event at Dome C, East Antarctica. *The Cryosphere*, 20, 1025–1046, https://doi.org/10.5194/tc-20-1025-2026.

Gorodetskaya, I. V., T. Silva, H. Schmithüsen, and N. Hirasawa, 2020: Atmospheric River Signatures in Radiosonde Profiles and Reanalyses at the Dronning Maud Land Coast, East Antarctica. *Adv. Atmos. Sci.*, 37, 455–476, https://doi.org/10.1007/s00376-020-9221-8.

Terpstra, A., I. V. Gorodetskaya, and H. Sodemann, 2021: Linking Sub-Tropical Evaporation and Extreme Precipitation Over East Antarctica: An Atmospheric River Case Study. *Journal of Geophysical Research: Atmospheres*, 126, e2020JD033617, https://doi.org/10.1029/2020JD033617.

Wille, J. D., and Coauthors, 2024a: The Extraordinary March 2022 East Antarctica "Heat" Wave. Part I: Observations and Meteorological Drivers. *Journal of Climate*, 37, 757–778, https://doi.org/10.1175/JCLI-D-23-0175.1.

——, and Coauthors, 2024b: The Extraordinary March 2022 East Antarctica "Heat" Wave. Part II: Impacts on the Antarctic Ice Sheet. *Journal of Climate*, 37, 779–799, https://doi.org/10.1175/JCLI-D-23-0176.1.