Comments and Suggestions by REVIEWER 1

SUMMARY

Reviewer 1: This paper provides an overview of the recent HALO-$(AC)^3$ aircraft campaign highlighting the flight plans/strategy, measurements, and various measurement/sampling techniques of Arctic air masses. Some of the novelties of this study include quasi-Lagrangian measurements from eight warm-air intrusion (WAI) and twelve cold-air outbreak (CAO) cases, derived surface heating/cooling and moistening/drying estimates, comprehensive aerosol/CCN data, and estimates of mesoscale divergence using dropsondes released during circular flight patterns. The abstract is very well written, concise, and clearly conveys the novelties and (initial) results of the AC^3 campaign. The quasi-lagrangian sampling strategy is very clearly defined, thought out, and easy to follow in the text/results. The section on Arctic clouds nicely highlights cloud phase as a function of the underlying surface (open water versus sea ice) as well as a simultaneous retrieval of effective radius for both ice crystals and liquid drops. These results, in my view, appropriately highlight and contextualize the various datasets as well as set the table for a number of planned (and likely interdisciplinary) analyses across a wide array of Arctic climate science sub-disciplines. Aside from a couple of very minor comments (indicated in the Specific Comments) and with a few of the figures being quite "busy" with lines and markers, every figure – in my view – is justified in its content with each figure adding very clear and rich context to the paper. Another strength of this manuscript is that, given volume of data and analysis in this manuscript, all sources of uncertainty (e.g., LWP and snowfall) are well characterized and quantified.

This is a commendable effort by all authors and contributors. For a very lengthy manuscript with 17 figures and 3 appendices, this was a very fun read with a lot of concise, "to-the-point" information that many sub-disciplines within the Arctic science community will be eager to read. I liken this manuscript to a fine 7-course dinner: it may take a while before you're finished, but every course delivers masterfully crafted dishes by world-class chefs with each dish delivering a palette of flavors certain to whet every appetite in the Arctic climate community. The manuscript in its present form is perfect in the sense that it captures just the right amount of detail (in my view) for an overview paper. While I have a number of very specific comments that would improve clarity in a few spots, they are extremely minor and can be addressed quickly without the need for a second review. I have no general concerns/comments for this manuscript, and overall, I believe this manuscript is publishable in its present form to Atmospheric Chemistry and Physics.

I look forward to many more in-depth studies following and building upon the excellent work presented in this manuscript.

Reply: *Thank you for your general comments, which we greatly appreciate. Also, thanks a lot for your very useful specific suggestions. We did our best to carefully consider all your remarks.*

SPECIFIC COMMENTS

Reviewer 1: L23-24: "... was more than 1.5 K warmer than during pre-industrial times" though it's stated "Data published by the Copernicus Climate Change Service show...", this statement needs a citable reference.

Reply: *We give the following web site as a reference for this statement:* *https://climate.copernicus.eu/global-climate-highlights-2023*

The corresponding sentence has been changed, such that it is more precise now:

"The data published by the Copernicus Climate Change Service show that on almost 50 % of days in 2023, the anthropogenic warming exceeded the values of the pre-industrial period (1850-1900) by at least 1.5 K (https://climate.copernicus.eu/global-climate-highlights-2023)."

Reviewer 1: L24: "numerous feedback mechanisms in the Earth's climate system" it would be good to list 2-3 or so of these feedback mechanisms here.

Reply: *We have added one sentence listing several Arctic-relevant feedback mechanisms here:*

"Prominent examples of these Arctic-relevant feedback loops are the Planck, water vapor, surface albedo, and cloud effects."

Reviewer 1: L44: A reference or two here would be good.

Reply: *Yes, we have included two references to substantiate this statement:*

- *Alvarez, J., Yumashev, D., and Whiteman, G.: A framework for assessing the economic impacts of Arctic change, Ambio, **49**, 407–418, https://doi.org/10.1007/s13280-019-01211-z, 2020.*
- *Melia, N., Haines, K., and Hawkins, E.: Sea ice decline and 21st century trans-Arctic shipping routes, Geophysical Research Letters, 43, 9720–9728, https://doi.org/10.1002/2016gl069315, 2016.*

Reviewer 1: L105: This is a very lengthy introduction, but a necessary one as each paragraph here has a clear focus and motivation for the AC3 campaign.

Reply: *We agree and have not changed this part.*

Reviewer 1: L124: Add latitude/longitude coordinates for Kiruna and Longyearbyen here.

Reply: *We have included the geographical coordinates of Longyearbyen (78.24° N, 15.49° E) and Kiruna (67.85° N, 20.22° E).*

Reviewer 1: L134: Add latitude/longitude coordinates for Ny-Ålesund.

Reply: *We have added the geographical coordinates of Ny- Ålesund: 78.92°N, 11.92°E.*

Reviewer 1: Section 2, like the introduction, is very well structured and written.

Reply: *Again, we agree.*

Reviewer 1: L171: Casual readers may not fully understand what a "Lagrangian" frame of reference is and how it ties into the sampling strategy described in this paragraph. A sentence to open up this paragraph describing what "Lagrangian" is, in my view, would lead the rest of this paragraph better and make the sampling strategy clearer to the reader in its objective.

Reply: *Thanks, we now introduced the term "Langrangian" even earlier, in the introduction, right after the first mention of the term. We have changed/added the text in the "Introduction" section as follows:*

"As a consequence, dedicated observations of WAIs and CAOs would be helpful to improve the model capabilities in order to realistically represent processes that determine air mass transformations during meridional transports into and out of the Arctic (Wendisch et al. 2021). Lagrangian measurements are well suited for this purpose. The Lagrangian approach assumes that the observations are made in relation to a coordinate system that moves together with the air mass. In this way, the changes in the properties of the same air parcel can be observed along its pathway. In contrast, the observations from a Eulerian perspective refer to a locally fixed coordinate system, so that the properties of successive, different air parcels are measured from a fixed position as a time series."

Reviewer 1: L174: "Because of their..." I would lead this sentence with "For example, ..." as this would more clearly lead the reader into a discussion of balloon-related drawbacks described in the previous sentence.

Reply: *Done.*

Reviewer 1: Figure 2 Caption: Recommend changing "enables to observe the changes" to "enables observational changes"

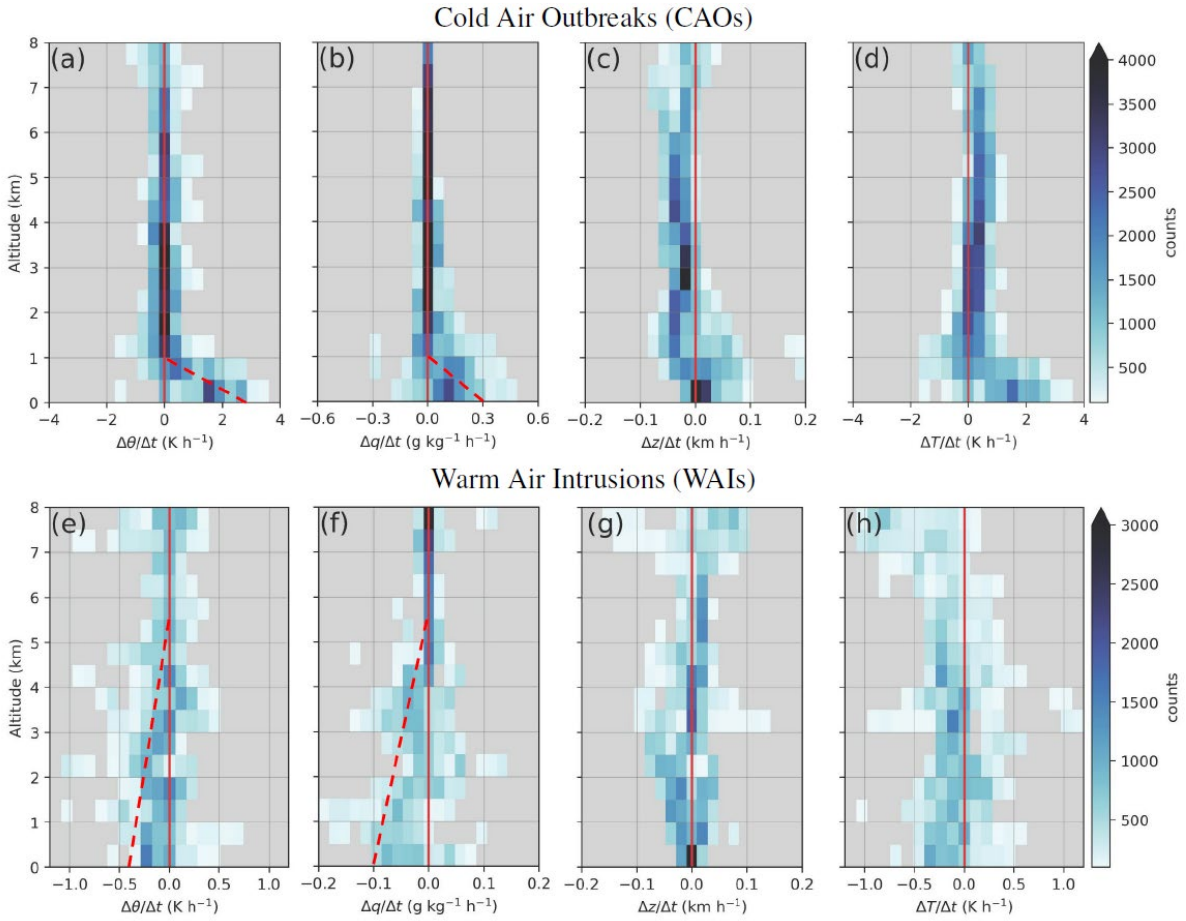
Reply: *We have replaced "enables to observe the changes" with "enables observing the changes". Otherwise we would not meet what we intend to say.*

Reviewer 1: L248: I am slightly confused by the writing here – what do you mean by a "quality of possibilities"? I think "provides unprecedented quantity of possibilities" would work here.

Reply: *Indeed, your suggestion makes perfect sense. Thanks, we have modified the text accordingly.*

Reviewer 1: Figure 5: This is a very well-constructed figure that clearly contrasts CAOs with WAIs.

Reply: *We agree. To make this even clearer we have modified the figure slightly, see below:*



Reviewer 1: L305: How exactly is the "ice growth process" inferred or done using measurements here?

Reply: *This has been realized by using in-situ measurements of ice crystal size distributions that are described in detail by Maherndl et al. (2024).*

Reviewer 1: L306: Can you point to or reference where "we also detect stronger riming"?

Reply: *Again, we refer to Maherndl et al. (2024) cited in our paper.*

Reviewer 1: Figure 6: Very picky comment here... "weak" should be capitalized in the Figure Title.

Reply: *Done. We appreciate that you are picky, because we are picky ourselves.*

Reviewer 1: L317-319: Very interesting result!

Reply: *We agree.*

Reviewer 1: Figure 7: I love the setup of this figure – it is definitely one of the most informative figures I've ever seen relating ice index and distance from the ice edge to actual cloud morphology. I hope to see versions of this figure in your future papers.

Reply: *We are working on more detailed papers on this topic.*

Reviewer 1: Figure 8 caption: Is it really necessary to call this a "Shapiro-Keyser cyclone" here? I think it would be better if this were referenced (including the citation) in the main text rather than the figure caption.

Reply: *We have shifted this part into the main text, following your advice.*

Reviewer 1: L374 and Figure 10 caption: One of the other prevailing cloud phase/microphysics algorithms for ground-based cloud remote sensors follows the widely-used Shupe et al. (2008, and references therein). I think it would be useful for the Arctic cloud/climate community to comment on how your algorithm compares with the Shupe et al. algorithm (and perhaps discuss

how a comparison of these algorithms might be done in a future AC3-related study which would also be very interesting!).

Shupe, M. D., and Coauthors, 2008: A Focus On Mixed-Phase Clouds. Bull. Amer. Meteor. Soc., 89, 1549–1562, https://doi.org/10.1175/2008BAMS2378.1.

Reply: *In the in-situ cloud community, there is no universally applied definition of a mixed-phase cloud. Various methods, such as those described in Korolev et al. (2017), examine the ratio of liquid to ice in different ways and are strongly dependent on the in-situ cloud instruments used. The method we apply here has been validated using a Polar Nephelometer, which directly indicates the thermodynamic phase of cloud particles through their optical properties. This approach is particularly advantageous because particle sizing instruments normally require additional assumptions to differentiate between solid ice and liquid water.*

The new method for thermodynamic cloud phase classification presented in Moser et al. (2023) can be used to develop new retrieval algorithms or to validate existing remote sensing retrievals for the detection of Arctic mixed-phase clouds, such as discussed in Shupe et al. (2008). Since many data from remote sensing instruments and in-situ cloud probes were obtained in colocation during the HALO-(AC)^3 campaign, further studies on algorithms for the microphysical propertied of Arctic clouds will be investigated within the (AC)^3 project.

To consider this issue raised by the reviewer we have added one sentence (including corresponding references) after line 385:

"Furthermore, the method to detect thermodynamic phase in Arctic mixed-phase clouds with in-situ particle measurements as describes in Moser et al. (2023) will be used to validate existing remote sensing algorithms, such as that of Shupe et al. (2008)."

References:

- *Shupe et al., 2008: https://doi.org/10.1175/2008BAMS2378.1*
- *Korolev et al. 2017: https://doi.org/10.1175/AMSMONOGRAPHS-D-17-0001.1*
- *Moser et al. 2023: https://doi.org/10.5194/acp-23-7257-2023*

Reviewer 1: L382: Just say "Future studies" rather than "near future studies".

Reply: *Done.*

Reviewer 1: L390: Following my previous comment for L374, this might be a good spot to discuss potential differences in these algorithms.

Reply: *Done above, hopefully.*

Reviewer 1: L430: How typical are RHi values of 140%? Might be good to add a reference or two here for comparison sake.

Reply: *High values of supersaturation (larger than 140 %) within cirrus clouds have also been reported by former studies (e.g., Comstock et al., 2004; Groß et al., 2014; Krämer et al., 2020). However, they did not focus on cirrus clouds in the Arctic. In contrast, Gierens et al. (2020) used radiosonde measurements for cirrus cloud studies in the Arctic and found high ice supersaturation; sometimes even exceeding 150%. Here are the respective references:*

- *Gierens, K. M., Wilhelm, L., Sommer, M., & Weaver, D. (2020). On ice supersaturation over the Arctic. Meteorologische Zeitschrift, 1-12.*
- *Krämer, M., Rolf, C., Spelten, N., Afchine, A., Fahey, D., Jensen, E., ... & Sourdeval, O. (2020). A microphysics guide to cirrus–Part 2: Climatologies of clouds and humidity from observations. Atmospheric Chemistry and Physics, 20(21), 12569-12608.*
- *Groß, S., Wirth, M., Schäfler, A., Fix, A., Kaufmann, S., & Voigt, C. (2014). Potential of airborne lidar measurements for cirrus cloud studies. Atmospheric Measurement Techniques Discussions, 7(4), 4033-4066.*
- *Comstock, J. M., Ackerman, T. P., & Turner, D. D. (2004). Evidence of high ice supersaturation in cirrus clouds using ARM Raman lidar measurements. Geophysical Research Letters, 31(11).*

We have reformulated the corresponding sentence as follows and added the reference:

"Even values exceeding the threshold of homogenous freezing have been found inside and around the WAI cirrus. This is in accordance with former findings of Gierens et al. (2020), who used radiosonde measurements to study cirrus clouds in the Arctic."

Reviewer 1: L455-456: I'd merge these two sentences.

Reply: *Done.*

Reviewer 1: L512-513: I agree with this conclusion.

Reply: *Thanks.*