Comments and Suggestions by REVIEWER 2

<u>Reviewer 2</u>: This manuscript gives an introduction to the quasi-Lagrangian sampling strategy performed during the HALO-(AC)3 campaign in order to study air mass transformations. Some example applications/first results are described, covering the observations during air mass transformation in warm-air intrusion (WAI) and cold-air outbreak (CAO) cases, Arctic cloud and aerosol properties, and measurements of mesoscale divergence and subsidence. In general, it is a very well written manuscript, providing a good overview of the quasi-Lagrangian sampling strategy and its application. I do have a few specific/minor comments for improving the clarity in some places, apart from these, I believe that the manuscript will be publishable.

<u>Reply</u>: *Thanks a lot for your very useful review. We did our best to carefully consider all your suggestions and remarks.*

<u>Reviewer 2</u>: line 60/footnote: Why do you restrict yourself to marine CAOs? Please explain and mention here.

<u>Reply</u>: *This restriction is determined by the $(AC)^3$ project, which excludes by purpose investigations related to land ice atmosphere interactions, for example in relation to Greenland. Instead, $(AC)^3$ is focusing on marine environments. We simply don't have the funding to cover the land masses in addition to the sea surface processes. To make this clear we have modified the footnote to:*

"In this paper we restrict ourselves to marine CAOs; our project does not investigate land surfaces such as the Greenland ice sheets."

<u>Reviewer 2</u>: ll 96-104: As you list previous attempts of Lagrangian measurements: What do these studies tell us here? Was their approach successful, did you copy their approach? Where there issues which you now tried to solve with your approach? What can we learn from these studies which is valuable here? Listing these is good, but what do they tell us for this study? Is there an added value we can gain from these studies?

<u>Reply</u>*: We were hesitant to claim that we are the first who have really successfully applied this approach during a major aircraft campaign, we leave this to judge by the readers. But in fact, there are only really few attempts of quasi-Lagrangian measurements applying aircraft and to our knowledge there are none in the Arctic yet. We have invested many efforts to realize this technique, and even during the campaign we could not be absolutely sure that we have succeeded. That became only evident after eventually analyzing the data after the campaign coming up with the results shown in Figure 4. The list and discussion of the previous attempts is important to give the reader an overview and to show the issues related to this approach. We do hope that our description will help the reader to evaluate the success of our quasi-Lagrangian technique that enables, for the first time, to quantitatively analyze the ability of models to represent air mass transformation during meridional transport into and out of the Arctic.*

Reviewer 2: line 133: Ehrlich et al., 2024 – as this paper is not yet published, not even submitted, I would strongly recommend making an according statement here: Ehrlich et al. (2024, to be submitted).

Reply: *We are confident to come up with a citable reference for the data paper soon enough before publication of this current manuscript. Meanwhile we follow your suggestion and cite the data paper with "Ehrlich et al. (2024) for Submission to Earth Syst. Sci. Data".*

Reviewer 2: line 134: AWIPEV – abbreviation?

Reply: *AWIPEV is actually not a classical abbreviation, but a mixture of the institute abbreviations (with an "I" falling by the wayside) and in this form the name of our station. For more explanation, we have replaced the corresponding sentence by:*

"Furthermore, intensive ground-based measurements were carried out at the permanent German-French AWIPEV research base operated by German Alfred Wegener Institute (AWI) and the French Polar Institute Emile Victor (IPEV) at Ny-Ålesund (Svalbard), including additional observations with a tethered balloon (Lonardi et al., 2024)."

Reviewer 2: Table 1: Dropsondes used in GTS: Are these taken from the HALO dropsondes only, or is it a mix of HALO and P5 dropsondes?

Reply*: Thanks for finding this missing but important detail. The direct transmission to GTS was setup for HALO only. Therefore, all sondes listed here for GTS are from HALO. We adjusted the table caption accordingly.*

Reviewer 2: Section 3.1: Calculation of trajectories: Were these trajectories calculated a) before the flight – used for detailed flight planning, b) during flight, using 'real' starting position of the planes – for real-time steering of the planes, or c) after flight – to check whether quasi-Lagrangian sampling has been achieved? The question is partly answered in the following subsections, but I think it would be good to state this clearly here.

Reply: *This question is clearly answered at the beginning of Section 3.2 where it belongs to from our point of view. There we write:*

"The actual computation of the forward-trajectories of the air mass parcels was performed using the Lagrangian analysis tool (LAGRANTO) (Sprenger et al. 2015). During the campaign, the trajectory calculations were based on the Integrated Forecast System (IFS) of the European Centre for Medium-Range Weather Forecasts (ECMWF) wind product. For processing the data after the campaign (for this paper) we have applied the Fifth Generation ECMWF Atmospheric Reanalysis (ERA5) (Hersbach et al. 2020)."

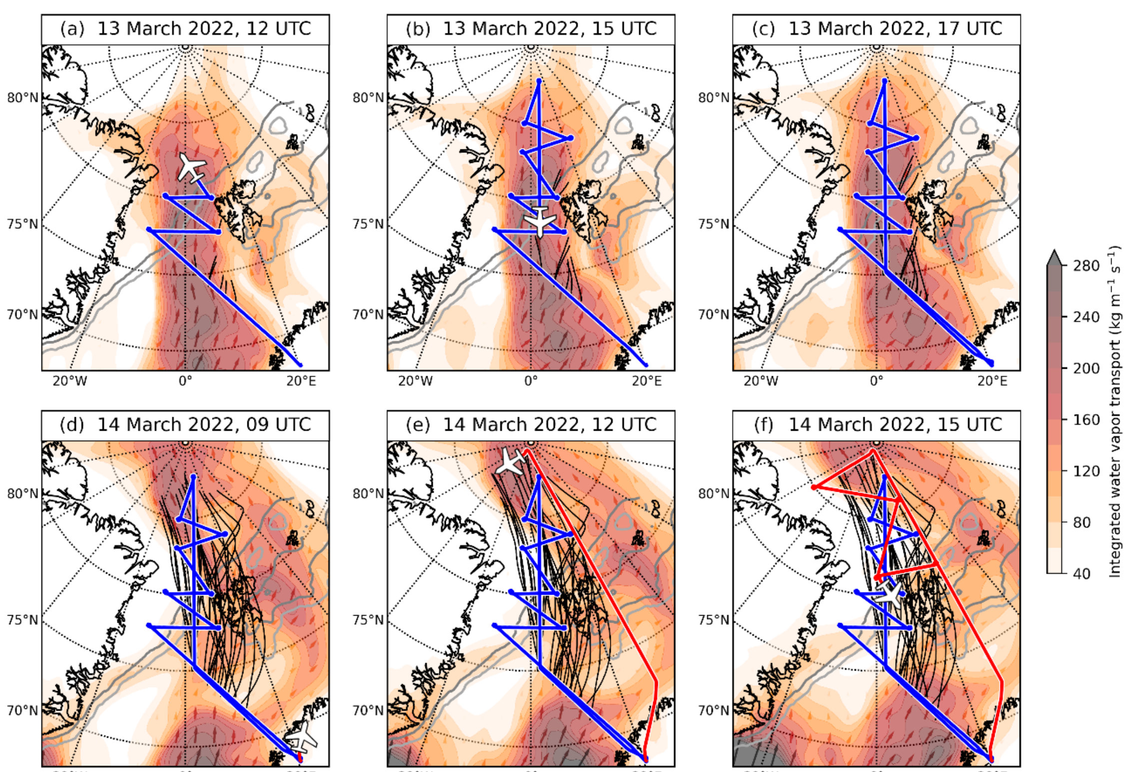
We would be hesitant to move that information to section 3.1. That might cause some confusion. We hope we could convince the reviewer.

Reviewer 2: Figure 2: Is HALO's remote sensing view on the air mass parcels (blue cubes) partly blocked by the P5, as it is flying stacked in between HALO and the air parcel? Or has this been taken into account for the collocated flight planning (e.g. adding a small spatial offset)?

Reply: *HALO and P5 have quite different flight speeds. Therefore we planned (or better we tried to plan) that both aircraft meet for a split of seconds somewhere in the middle of a flight leg. Anyway, even if the two aircraft would fly exactly above each other with the same speed, the influence of P5 on HALO remote sensing measurements in a distance between 8-10 km can safely be neglected.*

Reviewer 2: Figure 3: I would recommend to let the aircraft nose point into the direction of flight. E.g. in Fig. 3b it looks as if the aircraft is flying outbound of Kiruna, but I believe, it is on its way back, so the nose should better be pointing towards the right (or downwards right).

Reply: *Thanks for that hint; we have modified Figure 3 correspondingly. In addition, we have removed Figure 3c and instead implemented two new panels to increase the resolution of the time series and to avoid blank spaces. Here is the new version of this figure considering your comment:*



Reviewer 2: ll 266-268: Why treat open ocean and sea ice differently in CAO and WAI cases? Why disregard the cases above sea ice in the former?

Reply: *The air mass transformations governing WAIs and CAOs are dominated by different processes. In the case of CAOs, the major driver are the surface turbulent heat fluxes arising from the pronounced temperature and humidity gradient between surface and near-surface air layers over open ocean (1,2,3, references see below). This results in the strongest diabatic heating and moisture uptake of near-surface air layers in the first few hours of CAO evolution (4). While the pre-conditioning of Arctic air masses over closed sea ice through continuous diabatic cooling is crucial for the CAO formation, the air temperature change rates are typically one order of magnitude smaller over sea ice than later over open ocean (2,4).*

Contrary to CAOs, the processes driving air mass transformations in WAIs are typically more diverse. WAIs have been categorized into turbulence-dominated vs. radiation-dominated (5), and both cases are further complicated in the presence of a marked polar dome (5,6). Turbulent processes within WAIs are modified not only by the high air temperature and humidity of the lower-latitude as compared to the surrounding local air masses, but also the characteristic presence of thick, often stacked cloud layers (7,8,9,10). Thus, air mass tranformations in WAI flows during poleward transport can take place both over open ocean, the marginal sea ice zone, as well as over sea ice, and we would not want to miss the changes happening over all those different surface types.

We have added the following sentences to the manuscript elaborating this procedure of treating open ocean and sea ice differently in CAO and WAI cases.:

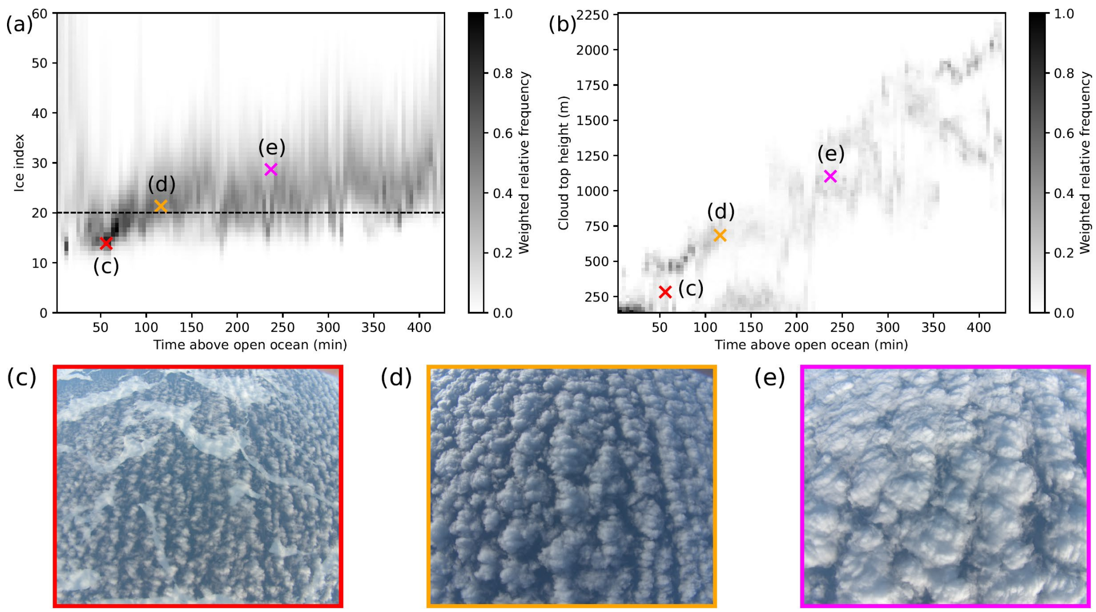
"In CAOs, major air mass transformations occur over the open ocean due to intense surface turbulent heat fluxes driven by temperature and humidity gradients, whereas the preconditioning over Arctic sea ice typically involves rates one order of magnitude smaller (2,4). Thus, in this article we focus only on the processes setting in over open ocean in case of CAOs. On the contrary, during WAIs intense air mass transformations through turbulent, radiative, and cloud processes can set in over open ocean, the marginal sea ice zone, as well as the sea ice (7, 8, 5). Therefore, we do not restrain the analysis of air temperature and moisture changes during WAIs to any surface type."

References:

(1) Brümmer et al. 1996 (10.1007/BF00119014)
(2) Papritz and Spengler 2017 (0.1175/JCLI-D-16-0605.1)
(3) Dahlke et al. 2022 (10.1029/2021JD035741)
(4) Kirbus et al. 2024 (10.5194/acp-24-3883-2024)
(5) You et al. 2022 (10.5194/acp-22-8037-2022)
(6) Komatsu et al. 2018 (10.1038/s41598-018-21159-6)
(7) Woods et al. 2016 (10.1175/jcli-d-15-0773.1)
(8) Johansson et al. 2017 (10.1002/2017gl072687)
(9) Kirbus et al. 2023 (10.3389/feart.2023.1147848)
(10) Dekoutsidis et al. 2024 (10.5194/acp-24-5971-2024)

<u>Reviewer 2</u>: Figure 7: There seem to be some white boxes overlaying some of the subfigures: "(a)" and "(b)" is only displayed partly, some of the y-axis annotation of subfigure (b) are partly gone, the indication of cases (e) in subfigure (a) and case (c) in subfigure (b) are only partial.

<u>Reply</u>: *There seems to be a technical issue, the figure we have included in the paper is copied here.*



<u>Reviewer 2</u>: line 409: "thin ice of nilas"? What is nilas?

<u>Reply</u>: *Nilas is a common term that comprises the "young sea ice of a few centimeters thickness". To make this clear we have replaced the corresponding original sentence by an extended version, which reads:*

"Beyond 40 km distance, the emitted radiation is governed by the surface, which is characterized by a mixture of pack ice and leads with relatively warm open water and <u>young sea ice of a few centimeters thickness (nilas)</u>, whose surface is also warmer than the surfaces of pack ice and cirrus. Thus, we see an increase of the emitted upward radiance in this region."

<u>Reviewer 2</u>: Figure 13: I would prefer if the colour scales also mention what property/variable they are showing. Secondly, the colour scale between subfigure a/b and c looks like it would belong to subfigures a and b, but I believe it does belong to subfigure c? If so, please reorder the figure to make this clearer; maybe place the colour scale on the right hand side of subfigure c? Also, in the figure, I can only spot instances where the occurrences (?) reach about or a bit more than 1000, while the scale goes up to 10000. Is that necessary? Otherwise, I would recommend to not extend so far, then also differences in the 30 – 100 value range (green to yellow transition) would become more visible. For all three subfigures: please consider changing the colour table ("end the rainbow"): Generally, it is advised to choose colour blind-friendly colour schemes, and the rainbow scheme is unfortunately not one of those (among other shortcomings of this colour table, see e.g. the open letter to the scientific community here: https://www.climate-lab-book.ac.uk/2014/end-of-the-rainbow/).

Reply: *Thanks for this comment; we have revised the figure correspondingly. We changed color table and rearranged the Figure but we had to keep the large values in the right scale. This is an automatic scale adapted to the maximum values (even if their occurrence is little). Here is the adapted figure:*

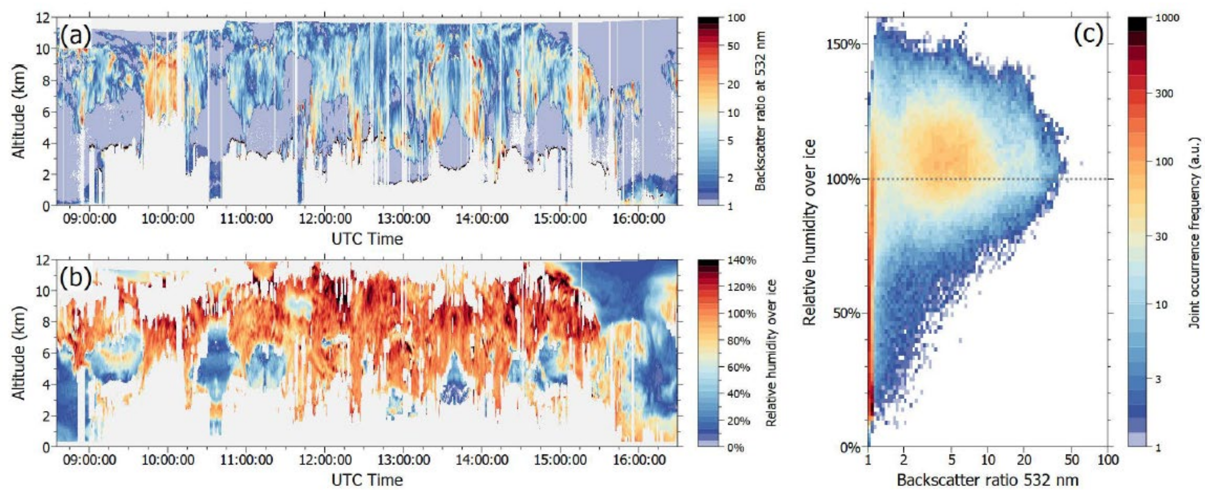


Figure 13. Cross-section of (a) backscatter ratio at 532 nm, and (b) relative humidity with respect to ice (RHi) for RF03 on 13 March 2022 during a WAI. (c) shows a histogram of joint occurrence of RHi and backscatter ratio at 532 nm. The relative humidity was calculated from WALES water vapor measurements and model temperature field.

Reviewer 2: lines 450-452: How can you be sure that the aerosol particles that were observed below and above the cloud are cloud droplet residuals (CDR)? Or do you mean that you compared the CDR properties (from within clouds) to aerosol properties above and below cloud? Please clarify/rephrase.

Reply: *The Reviewer is correct, the sentence has been revised to "We have compared the CDR aerosol properties to those of ambient particles collected in the ABL (below cloud) and in the free troposphere (above cloud)".*

Reviewer 2: Figure 15: How were the size distributions normalised, in what respect?

Reply: *Again, we would like to thank the Reviewer for his careful comments. We have added the missing information about the normalization in the caption of Figure 15: We have replaced*

"Normalized number size distribution of cloud droplet residuals (CDR) …" by

"Number size distributions <u>normalized by the respective number concentration</u> of cloud droplet residuals (CDR) …"

<u>Reviewer 2</u>: Figure 17 b-e: While you indicate times for ERA5 in the figure labels, could you also do so for the HALO/P5 lines? subfigure d) – The label indicates a green colour for the P5, in the plot, I can only find a red line, please check (maybe worth checking all figures again for colourblind-friendliness).

<u>Reply</u>: *In the revised figure we have now indicated times for ERA5 and HALO/P5 in the figure labels, thanks for this hint. The label for P5 in panel d is now in red, as indicated in the caption. Here is the revised version of the figure:*

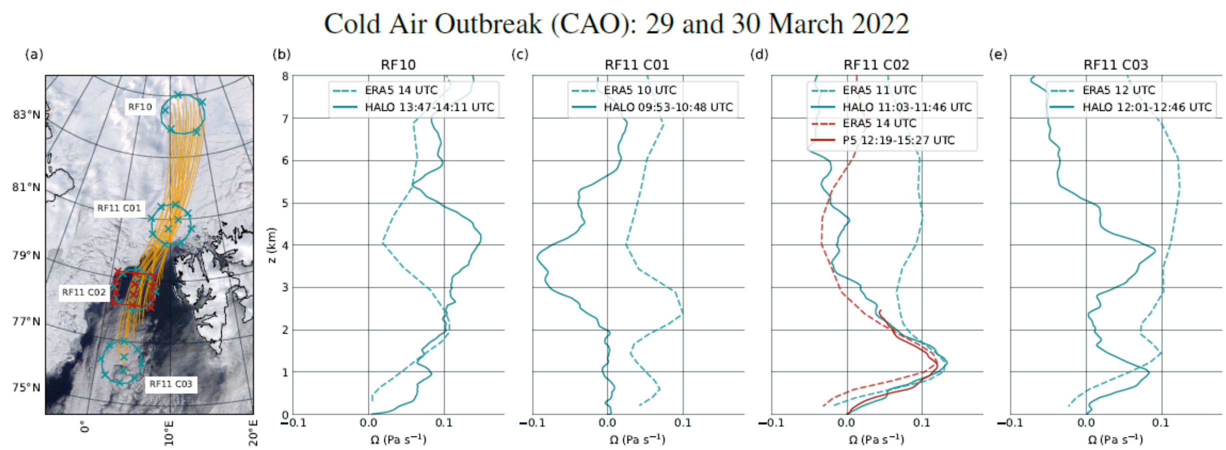


Figure 17. (a) Overview of mesoscale flight patterns flown by HALO (green circles) and P5 (red square pattern) sampling a low-level air mass on 29 and 30 March 2022 at four locations along its southbound trajectory (yellow lines). Dropsonde launch locations are marked by crosses (green if dropped by HALO, red crosses for sondes dropped by P5). (b)-(e) Profiles of pressure velocity Ω calculated from dropsonde data (time of first and last dropsonde launch indicated) released from HALO and P5 (solid lines) and ERA5 reanalysis data (dashed).

<u>Reviewer 2</u>: Appendices: While I understand that these results might be very interesting, the link to the main paper is not clear to me. They get barely mentioned (just in the introduction of Section 4 ("In the three appendices, we add partly preliminary, but nonetheless very interesting supplementary discussion and results from the HALO–(AC)3 campaign"), but seem otherwise disconnected. As the manuscript is already very long, I am not convinced that these appendices are necessary. So, maybe consider removing these. What is their link to the main aim of the paper (quasi-lagrangian observations), and what value do they add in that regard?

<u>Reply</u>: *We agree and have deleted the Appendix. Instead, we have included some sentences in the outlook of the manuscript. They read as follows:*

- *We will investigate the hypothesis that a secondary circulation acts to spread out moisture from the initial river-like intrusion in the cross-flow direction. This hypothesized circulation consists of uplift in the core of the intrusions, divergence in the upper troposphere above the core, and convergence and subsidence of drier air on the flanks of the intrusion. We will investigate the typical structure of the atmospheric moisture field, and how it evolves during a WAI including a discussion on what processes drive this development.*
- *The particular mode structure of the Arctic radiant energy budget (REB) will be analyzed as a function of altitude, different surface type (sea ice or open ocean), cloudy or cloud-free conditions, and thermodynamic properties (temperature lapse rate, horizontal temperature gradient between sea ice and open ocean). The observations will be confronted with model results that often struggle to correctly represent the mode structure of the REB, e.g., due to limitations in the treatment of sub-grid processes including clouds and the sea ice albedo. Therefore, detailed observation–model comparisons are envisioned to identify potential misrepresentations of properties affecting the REB.*
- *We are about to study an extraordinary CAO case observed during HALO-(AC)³. We will integrate our data obtained during two CAO events with measurements following approximately a North-South trajectory (29 March and 9 April 2022) with literature data. The 9 April case was extraordinary for two reasons. Firstly, it was characterized by cloud-free conditions along the entire 180 km North-South flight track across the MIZ to the open ocean, which is very rare and unusual. Only at the southernmost position, convective clouds appeared. Secondly, the southernmost position was influenced by the front of a polar low, which was a remnant of a polar low over Fram Strait on the preceding day. We will discuss how the results of our observations on these two dates fit to earlier measurements.*

Reviewer 2: Figure 20: A legend would be nice.

Reply: *Again, this seems to be a technical problem. However, because the Appendix has been removed, this figure is not included in the manuscript anyways.*