Response to the comments from Anonymous Referee 2 for the submitted ACP paper: ´Dorff, H. et al. 2023: Observability of Moisture Transport Divergence in Arctic Atmospheric Rivers by Dropsondes

Superior Erratum:

With the aid of the reviewer's remarks concerning the frontal gradients in moisture transport divergence and the emerging revision of our manuscript, we identified erroneous results in our divergence calculation. In specific, we accidently did not calculate the wind divergence from using both u, v components but considered the absolute values of wind speed. By that our divergence results were direction-independent. In order to conduct a component-wise divergence calculation, we now had to rotate the u, v components in CARRA, as they are oriented along the local grid rotation and not the zonal/meridional direction. In doing so, the results in chapter 5 and chapter 6 (Figure 12-15) have changed moderately. In the response sections that refer to the respective manuscript sections, you will find the updated figures, alongside a specification of differences to the preprint results. In the remainder of this response, our updated results are already included when we present corresponding snippets of the updated manuscript paragraphs.

Prefaces:

We thank the ACP associating editor, Geraint Vaughan, as well as the Anonymous Referee #2, for this inspiring review. Please find below our responses (in standard font) to the remarks from the Anonymous Referee #2 (in *italics*). We structured this response in such a way that comments on the most important text blocks for improvement (e.g. motivation) are bundled and distinguishable from each other. In this response, we occasionally refer to our Author's responses for Referee 1 (AC1), because several answers in AC1 also consider the remarks given from Referee 2 and we intend to avoid too much repetition.
We reserve the right to apply minor changes to the here modified text snippets for the final revised manuscript in order to achieve even more concise phrasing and to guarantee grammatical correctness.

Responses to Reviewer 1:

General

This paper provides a contribution to advancing our understanding of arctic atmospheric rivers by presenting an analysis of them using different reanalysis products, and suggesting ideal targeting strategies for the purpose of understanding and closing the moisture budget.
Response: We want to thank you for the detailed and inspiring feedback. Given your remarks, we realize that the perspective of our study, in particular, should be carved out more clearly. We are confident that such a specification enables to significantly improve the manuscript readability and clarity. Accordingly, in our revision, we focus on improving the readability by a more elaborated structure which provides more precise motivation for sampling of ARs from airborne dropsondes.

Major

In general, I think it is important for this paper to provide some additional context and motivation for the exercise of synthetic sampling.
Response: We agree that the preprint lacks a well-elaborated motivation for our sonde sampling approach with respect to arctic ARs. Therefore, we will carefully rewrite the introduction which, based on the reviewer remarks, we identified as one of the major weaknesses of our manuscript.

In detail, we specify our changes in structuring the motivation in the Author's Response for Referee 1 (from now on denoted as AC1). At this point, we summarize some of the changes that we declare as most relevant according to your review:

- The first paragraph will state more explicitly the presence and impact of Atmospheric Rivers (ARs) in the Arctic. Given your recommendation for more information about Arctic conditions, we will now refer to a broader collection of studies with respect to the Arctic and, in particular, concretize their findings relevant for our motivation, rather than only list relevant literature (as done before). The second paragraph characterizes the moisture transport (IVT) and its divergence in ARs, how this becomes relevant for the transformation of moist air masses, and how IVT shapes the regional moisture patterns in the Arctic (Nygard et al., 2020). Finally, it disentangles the issue and research gap, which is the lack of quantitative estimates for IVT divergence within Arctic ARs.
- "*Is there a possibility for in situ sampling of arctic ARs? Is the paper calling for this capability as a requirement for us to meaningfully further our understanding in this region?*" **Response:** As stated before, the second paragraph serves as a logical transition to the following paragraph describing the required measurement strategies to derive IVT and highlighting the need of in-situ sampling to obtain the moisture transport throughout the troposphere. The third paragraph will thus address your point in more detail: We mention that the observational radiosonde network in the Arctic (Dufour et al, 2016) allows the derivation of IVT divergence into the Arctic, but argue that this network is too coarse to resolve IVT variability and divergence within single AR events. This motivates the use of dropsondes from research aircraft specified in the following. We are confident that this argumentation better highlights the ability of in-situ sampling which serves as a prerequisite to be able to meaningfully expand our knowledge of moisture transport in arctic ARs.
- Both referee reviews demonstrate that the manuscript requires an improved motivation for our choice of a synthetic sampling approach. Therefore, the research focus and overarching motivation of our feasibility study are introduced earlier (beginning of 4th paragraph). In particular, we mention that there currently exist arctic airborne flight campaigns using a long-range research aircraft proposed by Wendisch et al. (2021). This fact motivates a pre-assessment of the sonde-based observability of moisture transport divergence in arctic ARs. Not only, this will improve the interpretation of sonde-based observations gained in the HALO-(AC)3 campaign (Wendisch et al., 2021; Walbröl et al., 2023) which are currently under processing, our feasibility study also aims at facilitating future flight mission planning that has a similar special focus on high-latitude ARs, e.g. like the NAWDIC campaign: https://internal.wavestoweather.de/campaign/projects/nawdic/wiki)
- The changed order in which we will introduce our research questions sequentially, rather than at the end of the introduction as in the preprint, is intended to strengthen our argumentation. In doing so, we expect that this leads to more clarity why we have chosen a synthetic approach in investigating the arctic ARs.

How would this papers' findings be different if the synthetic sampling wasn't a part of it? Does this framing potentially distract from the findings regarding the structure of arctic ARs?

Response: We fully agree that a study purely dealing with the structure of arctic ARs using reanalyses or model simulations will represent a very fruitful scientific contribution. Nonetheless, we admit that we, the authors, are mostly situated in the observational scientific community and are confronted with the necessity of airborne data in arctic ARs. Since we do expect several studies to emerge from the previous HALO-(AC)³ flight campaign and upcoming campaigns with respect to arctic/ high-latitude ARs, we certainly see a benefit in our approach for future studies. For instance, in the HALO-(AC)³ special issue of ACP, we envision a contribution of the novel airborne derivation of all moisture budget components (including IVT divergence) in an arctic AR that was observed during HALO-(AC)³ (Walbröl et al., 2023). For this, our feasibility study can serve as a preparational study that quantifies the magnitude of airborne misrepresentation in sonde-based moisture transport divergence. Correspondingly,

our title was chosen in a way that it immediately becomes clear that our focus is in the observability.
Nonetheless, we will take your valid suggestion into account in the manuscript. Our conclusions will now emphasize the ability of investigating arctic ARs in a more general perspective using CARRA. We will promote follow-up studies that attribute dynamic and thermodynamic conditions to the AR characteristics: "[…] since we include a large variability of synoptic AR patterns but a small sample, we suggest statistical analyses involving a larger amount of AR events. Such statistics can foster our understanding of moisture transport divergence pattern in arctic ARs and attribute them to the dynamic and thermodynamic atmospheric conditions. For such follow-up purposes, CARRA represents a very suitable reanalysis framework […] "

I suggest the authors consider strengthening their case for structuring the paper in this way and referring to more papers studying arctic ARs and their structure in addition to observational studies covering the midlatitudes if they would like to keep this framing.
Response: We will restructure our introduction in this way (see above). We will include more literature findings from arctic ARs, not only in the introduction but also when comparing our results to polar AR characteristics investigated in other studies, such as Terpstra et al. (2021); Viceto et al., (2022); Lauer et al (2023). In this regard, please find detailed manuscript modifications in the AC1 (especially for Section 3 and 4). In compliance with the remarks from Referee 1, we elaborate on the results concerning the general structure of arctic ARs in more detail in the respective sections, before moving on to the sonde-based representation. This also applies to the presentation of our arctic AR cases, where we manifold the discussion of the synoptic conditions causing the ARs to reach the Arctic (see AC1, Sect. 2). In Sect 3.1 (originally Sect 4.1), we compare the arctic AR-IVT shapes in more detail with those from mid-latitude cases. We use this knowledge as a prerequisite for the following examination of the sonde-based AR-IVT representation. Not only for general AR characteristics, but also for the sonde-based representation, we will enlarge and concretize the comparison to mid-latitude based studies (e.g. in the relabeled Sect 2.2, 3.1, 3.4, 4.1, 4.2). You can find concrete examples given in AC1 that consider your comment of including more analysis of the phenomenology of arctic ARs in contrast to mid-latitude ARs. By this, we aim to consider your comment of including mid-latitude based AR knowledge. Yet, we would like to keep our original framing/scientific perspective in principle. Nonetheless, we already see a clear progress of the manuscript in providing more details of the general arctic AR characteristics. These details will additionally improve our argumentation and discussion in our sonde-based assessment.

I suggest considering a reframing where the authors discuss what can be learned about arctic AR structure from appropriate reanalyses at different resolutions, and then recommend sampling strategies to verify/supplement this knowledge.
Response: For our purposes, we see a certain risk in changing the whole structure in this direction, because then the main objective of this study (which is the assessment of sonde-based IVT observability and uncertainties in the sonde-based representation) would be underrepresented or the paper could become too long and overloaded. Instead, we will sketch the impact of the reanalysis resolution on the arctic AR structure in more detail in Sect. 3.1 (originally 4.1) and will refer to the current study of Viceto et al. (2022) in which they conducted a reanalysis comparison in a case study of arctic ARs. This will be included in two paragraphs as follows:
"[…] we recognize the bell-shaped IVT inside the AR from both, CARRA and forcing ERA5. Within the cross-section centre which we declare as the AR core (Sect. 2.5), CARRA, however, shows stronger moisture transport with a more pronounced IVT maximum > 500 kg $m^{-1}s^{-1}$. Moreover, CARRA with its higher horizontal resolution depicts more small-scale structures of the AR moisture transport. In particular, CARRA increases the cross-section IVT variability for this case."
"[…] Viceto et al. (2022) further documented the improved representation of arctic AR characteristics in ERA5 against coarser reanalysis data. In our comparison, the location and horizontal pattern of the ARs in CARRA agree quite well with ERA5 (not shown). For all cross-

sections, we ascertain plausible IVT values from CARRA with respect to ERA5. In particular, we highlight that maximum (mean) values of IVT per cross-section increase by roughly 9 % (8 %) from ERA5 to CARRA on average. CARRA further increases the IVT variability by roughly 11 %. We attribute this to the higher horizontal resolution than in ERA5."

Do your results regarding non-instantaneous sampling change if you take into account the observations in time and space where and when they occur, as is possible in many assimilation systems now?
Response: To prevent any misunderstanding, we remind that we interpolate the reanalysis data in time and space onto the flight track and compare this to the reanalysis output at centered hour (denoted as instantaneous snapshot).
Current methods to derive divergence from airborne soundings require atmospheric stationarity (e.g. Bony and Stevens, 2019), which in turn can only be idealized in observations. To circumvent this issue, Norris et al. (2020) conducted a time-to-space adjustment of their sonde profiles. In our study, we aim to address the impact of instationarity for our divergence calculations by research question Q4. Here, we clearly see the limitations in the sonde-based derivation of moisture transport divergence from our flight pattern.
Still, your point is a very useful recommendation for future steps in improving the regression methods to a multivariate regression involving the temporal component. For our purposes in which we refer to the state of the art in the calculation assumptions for the observations, assimilation methods remain out of scope of this study.
From the recent flight campaign HALO-(AC)3, we know that the dropsonde data has been integrated into the Global Telecommunications System and used for assimilation in ERA5. The upcoming investigation of the HALO-(AC)^3 observations in arctic ARs should certainly take this into account. So far, we can only speculate about the outcome but see a very good agreement between ERA5 and the dropsondes due to the assimilation.

I very much like how the authors identify key questions and then revisit them in the summary with their answers to synthesize the paper for the readers.
Response: We are glad that the key questions are considered as suitable guideline throughout our manuscript. Under consideration of the remarks from Referee 1, the motivation improved unravelling and identifying our key questions. As mentioned in AC1, the synthesis of our answers now has a more precise focus on implications for future airborne measurement strategies.

Minor

Line 24 – flood may not be the best word choice here, please revisit ("affect"?)
Response: We will rephrase the first sentence and also include a concise definition of Atmospheric Rivers (ARs) as follows:
"Atmospheric rivers (ARs), which are elongated (>2000 km in length) but narrow (<1000 km in width) water vapour rich corridors causing high moisture transport, occasionally enter the Arctic."

Figure 1, Figure 4: locate us in space with lat/lon
Response: We will add a lat/lon grid accordingly

Figure 3 – suggest including a box in (a) to illustrate where the box in (b) comes from.
Response: We include a slight rectangle in top view illustration (a) and renamed the boxes in (b) from "sections" to "corridors" in order to guarantee consistency between both subfigures.

Line 252 – does this suggestion of 5 sondes at minimum depend on the AR width?
Response: Concerning both Referee remarks, we put more focus on actual sonde spacing (in distances) rather than number of sondes (see also AC1, Section 3.2). Therefore, we reformulate: "we emphasis that a minimum sounding spacing of 100-150 km has to be targeted for arctic ARs." This corresponds to 4-8 dropsondes for most of the AR widths in the range of

400-800 km. Like we will add in the respective discussions, the sounding spacing is not only affected by the AR width, but also by the steepness of IVT. For example, in wider but weaker ARs, a spacing of 150 km may be sufficient to accurately derive TIVT, but in a narrower but stronger AR (greater steepness of IVT) we recommend a spacing of at least 100 km.

Figure 6 – suggest this would be better presented as spatial interval to not require so much information regarding assumptions about plane speed etc. Indicate what the colors represent in the caption.
Response: The x-axis is changed to spatial intervals. Further information is given in AC1.

Line 268 – isn't this larger difference in q expected given the colder air?
Response: Yes, it is not surprising. Still, we want to emphasize the contrast to the winds that are in a comparable magnitude of order as in mid-latitude ARs. We will rephrase it as follows: "q is considerably lower due to the cooler air masses."

If the AR is more moist or more windy, does that affect the spacing requirements to fully capture the structure?
Response: So far, we cannot disentangle clear statements that a more windy AR requires more dropsondes than a more moist AR or vice-versa. But how we explain for our strongest AR event (AR3), the winds here were rather constant (and high) along the horizontal AR transect while the internal moisture plume was primarily responsible for the moisture transport variability. As an outlook, upcoming studies could investigate this in more detail in a larger sample.

Line 323 – constant winds in time or in space? Can you refer to one of your figures here?
Response: Here, we speak of the winds along the cross-sections, but will specify it correspondingly in the revised manuscript.

Figure 13 – what is the purpose of the colors in the box-whiskers plot?
Response: the colors refer to our colour-coded frontal sector composition as shown in Fig. 4. We will add this information in the Figure caption.

Editorial

A general quick read for grammar/word choice (clarity)/readability is warranted although generally the paper is in good shape. A few suggested changes are below (non-exhaustive).
Response: For its final form, we will conduct careful cross-reads to assure clarity and readability, and correctness in grammar and word choice.

Line 214 – suggest changing "infer" to "investigate"
Response: we will change the wording accordingly.

Line 219 – suggest rephrase "arises the question, how" to "raises the question whether".
Response: We will change it correspondingly.

Line 264 – suggest rephrase "contributes to IVT with roughly 50%" to "contains roughly 50% of the IVT magnitude"
Response: We will change it accordingly

Line 265 – remove "even"
Response: confirmed

Line 321 – suggest rephrase "are little coherent" to "exhibit little coherence"
Response: we will reformulate it accordingly

Line 348 – suggest rephrase “neither it considers” to “it considers neither”
Response: we will reformulate it accordingly

Figure 11 – suggest removing “corridors in the” from the caption
Response: We agree and will remove it from the caption