Third Point by Point Response for Manuscript, entitled 'Dorff, H. et al. 2023: Observability of Moisture Transport Divergence in Arctic Atmospheric Rivers by Dropsondes', for final publication

I) RESPONSE AND CHANGES TO THE COMMENTS FROM ANONYMOUS REFEREE 1 (AC1)

Preface:

We express our condolences that the Anonymous Referee #1 (AC1) invest this effort in continuously providing us these very detailed and helpful comments, which significantly improve the manuscript. We have adressed all remarks from AC1 and have adjusted all relevant text passages accordingly. The manuscript was read again as urged by both the Referee #1 and the handling editor. We additionally thank the editor for his continuous support.

We here only list the manuscript changes that require further clarification. All other edits are conducted as clearly suggested by AC1. Please find below our responses (in standard font) to the remarks from the Anonymous Referee #1 (in *italics*). Our changes/ modifications in the manuscript are specified **bold**. Line numbers of reviewer comments (grey) are now referred to the lines in the second revised manuscript (**black, bold**).

Specific responses to AC1:

*reconsidered after **major revisions***
This is my third review of Dorff et al. and I thank the authors for carefully addressing all of my comments. Although the manuscript improved, I still see deficits in the presentation of the results, especially grammatical edits would be valuable to get more clarity of the arguments. I went through the manuscript again and I suggest that the authors consider the comments carefully to improve the readability.
Response: First of all, we are very grateful for acknowledging the improvement of the manuscript and its consideration for publication. Given your feedback, we checked and modified all the given points listed above. Your remarks significantly helped out us to improve the readability. For all your comments, you will find our corresponding responses below.

L5/L70: It is not needed to change "error" everywhere but it should be defined what it is. If you talk about deviation then it should be explained from what?
Response/Modification (L5f): we rephrased: **"[…] we disentangle the sonde-based deviations from an ideal instantaneous IVT divergence, which result from undersampling by a limited number of sondes and from the flight duration.**"

L17: What is "their" referring to?
Response/Modification (L17f): changed to: **"we confirm the observability of IVT divergence with an uncertainty […]".**

L19/20: "Dedicated planning of (…) purposes (…)" makes no sense to me.
Response/Modification (L20f): We have rephrased: **"In order to realise the estimation of IVT divergence from dropsondes, flight planning should consider not only the positioning of the sonde, but also the minimisation of the flight duration."**

L21: Please clarify what you mean with this sentence! How can a prerequisite be used?
Response/Modification (L21f): We rephrased: **"Our benchmarks quantify sonde-based uncertainties as an essential preparatory work for the upcoming airborne closure of the moisture budget in arctic ARs."**

L58-60: What are the research flights proposed by Wendisch et al. and when will they be conducted?
Response/Modification: The research flights were planned for the HALO-(AC)³ campaign, and budget component analyses are currently under investigation and initially introduced in Wendisch et al. (2024, https://doi.org/10.5194/egusphere-2024-783). For the sake of brevity, we do not provide precise specifications in our manuscript, as all the information can be extracted from Wendisch et al. (2021).

L59 What does "It" refer to? I guess it remains unclear at point what you mean with "individual moisture and wind variability"
Response/Modification (L59f): We rephrased: **"We include a) […], a concretisation of the need for supplementary measurements based on spatial variability of moisture and wind."**

L67-71: These lines were revised since the last time but did not change for the better. Please revise a) "estimates (…) provide an initial estimate" and b) "spacing between the sonde spacing (…).Instead of referring four times to a "spacing", please give a value used in Ralph et al.
Response/Modifications (L67ff): We rephrased (a) as: **"Accurate airborne TIVT, juxtaposed for two separate AR cross-section legs, gives an initial estimate of IVT divergence in between both legs."** We rephrased L69f (b) as: **"When doubling the initial sonde spacing, which averaged about 80 km, by reducing the number of sondes included, they found a mean deviation of at least 5% for TIVT."**

L94-97: I still think you can be more specific about the findings in the referred papers and identify results of relevance to your work.
Response/Modification (L94ff): We rephrased the corresponding sentences as: **"Comparing two reanalyses, Guan et al. (2020) found differences in IVT divergence that, in the AR centres, reach up to 30 % the magnitude of IVT divergence itself. Norris et al. (2020) determined IVT divergence in a mid-latitude AR from dropsondes that allows interpreting the discrepancies of IVT divergence in ARs found by Guan et al. (2020). In particular, Norris et al. (2020) point to the large variability of IVT divergence at spatial scales of 50 km. This also has implications for sonde-based sampling best practices."**

L174: What does "synoptic compositions lead to AR dispersion" mean?
Response/Modification (L175): We rephrased: **"The synoptic compositions distribute the ARs over the North Atlantic and Arctic Ocean."**

L188-190: It is not clear how these findings are relevant and what Ralph et al. (2017) found. Instead I suggest the authors describe the conceptual model that the refer to in L191 and L194.
Response/Modification (L187ff): We readapted the connection of our statements as:
*"***Figure 2 shows some of the features that we know about mid-latitude ARs. Over the course of various research flight campaigns over the eastern Pacific, Ralph et al. (2017) have developed a conceptual scheme for the cross-sections of ARs. This scheme includes, for example, a low-level jet (LLJ), which is a strong low-level wind corridor (Ralph et al., 2004; Demirdjian et al., 2020). For the windy arctic AR events, e.g. AR3 and AR5, we detect the presence of LLJs stronger than 25 m s−1. The LLJ is located at a height of about 900 hPa, slightly lower than the mean height reported by Cobb et al.**

(2021) for mid-latitude ARs. As another feature of the AR cross-section scheme, Ralph et al. (2004) and Cordeira et al. (2013) found a horizontally slanted vertical structure of moisture transport in mid-latitude ARs from dropsondes and reanalyses. Ralph et al. (2017) confirmed the vertical interaction between the upper-level jet and the LLJ as a dominant effect for AR moisture transport. In Fig. 2, this is particularly evident for AR5. Here, moist air masses residing in the cyclonic warm conveyor belt are lifted over the cold front sector. The downward intrusion of air from the upper-level jets on the western flank causes the slanted structure of moisture transport.*"*

L195/196: I do not understand the sentence. What means "yield" in this context? "but missing there" where?

Response/Modification (L198ff): We have rephrased: **"In arctic ARs other than AR5, we find less agreement with the conceptual AR schemes. This is the case for the vertical structure of moisture, or the presence and the intensity of the LLJ, which is only strongly distinctive in AR1, AR3, AR5, AR7, but absent in all other cases."**

L213/214: The causality of the first sentence is unclear. "specific corridors" - I thought the AR itself is a corridor.

Response/Modification (L216ff): We have exchanged "corridor" by "area" at this point. Accordingly, we reformulated: **"To evaluate the airborne observability of ∇IVT within arctic ARs, we search for a suitable flight pattern. Such a pattern must capture well certain areas of the ARs. Flight tracks that enclose such areas, like circles, best allow divergence calculations and are often used for such purposes (e.g. Bony and Stevens, 2019)."**

We now use the term "flight corridor" to briefly refer to the area of the AR that is captured by the flight pattern. We find appropriate to call this region a flight corridor, even though the AR itself is occasionally described as a corridor in literature, too. To prevent misunderstandings, we clearly define this term in **L222f** as: **"For the sake of brevity, we speak of an AR flight corridor in the following, when we mean the area of the AR that is captured by the flight pattern."**

L225ff: The description "as ong as (…) Fig.3)" needs to be improved. What does it mean that you obtain the boundaries from the catalogue? What does "closer" means "less"? What is the "final distance"? What is that "visual inspection" about, which would also be done during a real field campaign flight planning process?

Response/Modification (L228ff): We have reformulated the paragraph as follows: **"We place the AR flight corridors close to the sea-ice edge. We orientate the cross-section legs orthogonal to the major IVT direction and extend the legs such that they transect the entire AR. One requirement is that the transect, and thus the lateral AR extension, is completely over open-ocean or sea-ice, so that we neglect landfalling regions of ARs. To obtain the spatial extent of the AR for a given case, we consider the shapes of the ARs defined in the AR catalogue of Guan et al. (2020). The meridional distance between the two cross-section legs is assured to be larger than 200 km but closer than half the lateral AR width. The decision for the placement and meridional distance of the cross-section legs is based on visual inspection of the reanalysis taking in particular the movement of the IVT filament into account. "**

For the real flight campaign, we recommend to include IVT forecasts into the flight planning and to look for AR like structures with IVT exceeding 100 $kgm^{-1}s^{-1}$. However, in this section of the manuscript, we do not find it useful to provide such information. We think that they rather belong in the outlook.

L235-237 and L239/240: I do not get the need of the 1 Hz resolution that is then reduced to 1 minute. I suggest deleting this information as it is confusing and seems not to be relevant here.
Response/Modification (L241ff): First, we only describe the flight performance, i.e how the aircraft position on its flight is defined. We rephrased: **"Based on the aforementioned flight performance, the aircraft location is represented in 1Hz resolution, as common remote-sensing products on research aircraft (e.g. Mech et al., 2014; Konow et al., 2019), that can complement dropsonde data, have a comparable time-resolution and require the information of the aircraft location.**

Then, we come to the point on how to project the meteorological data onto the "aircraft". For this, the reanalyses are interpolated in time onto 1min as we find this as good compromise to not overfit the data. From this coarser time evolving representation of the AR, we spatially interpolate via harvesine distances.

L241: Does "evolving representation of met. values" mean the temporally interpolated values?
Response/Modification (L248f): Yes, we changed it to: **"This spatio-temporally interpolated representation, […]"**

L242: Clarify what "assure model physics" means and delete "as".
Response/Modification: We meant that, while the models are tuned for consistency at their model output, this cannot be assured once we interpolate linearly among the quantities. Still, we agree that this sentence is confusing and not very relevant here. We have removed it for the sake of clarity.

L249: "Our (…) position" - What does that mean?
Response/Modification (L255f): We rephrased: "**The synthetic sondes profile the atmosphere fully-vertically from their release location. IVT is thus defined as the integral of the fixed vertical column from the respective reanalysis cells."**

L246-265 You explain two methods and should explain the reader which one is used or if they are compared, etc.:
Response/Modification: We added in **L259f** and **L266f**: **"To derive ∇IVT in AR flight corridors from sondes, we compare two approaches. The first one is a simplified approximation based on the derivation of the TIVT […] Given this limitation, Lenschow et al. (2007) alternatively suggests a regression-approach, which marks our second approach."**

Fig.5 If the x-axis runs from west to east, why is the cold post-frontal sector to the right?
Response/Modification: We are very sorry for this wrong statement. In fact, we wanted to say from east to west and corrected it accordingly.

L300: I suggest deleting "where our (…) ends". Change "our" to "the". Be more specific about "only categorize the prevailing air masses of an AR".
Response/Modification (L307ff): We rephrased: **"Both thresholds form the outer boundaries of the AR and of the pre-frontal and post-frontal sectors. Note that the sector terminologies are only a generalised categorisation of the surrounding air masses in the vicinity of the cold front inside ARs, but should not be viewed as a synoptic cold front identification."**

L302: It is unclear what "we (…) sectors" means. It is still unclear whether the release locations are selected at one particular time step (L305-307 is not clear on that) and how this is done in real case scenarios?

Response/Modification (310f): In Sect. 2.4, we mention that we place the sondes along the airborne continuous AR representation. We added in L300: **"All threshold criteria are applied to the continuous AR representation along the flight time, as in a realistic post-analysis from real research flights."**

In **L312ff**, we remind for this time perspective by: **"Using […], we locate the sondes along the flight time in a way that three sondes each in the in- and outflow cross-section span one out of the three pre-defined frontal sectors (Fig.6), and calculate its IVT divergence, respectively. Note there is probably more variation in the actual release position in real flights due to forecast uncentainities, even when the releases are planned using the threshold criteria based on forecasted IVT. However, we here stick to these pre-defined locations for comparability between the AR cases. "**

L312: What is "plane perspective" exactly meaning? Is this the temporally interpolated data?

Response/Modification (L325f): We rephrased: **"First, we stick to the vertically-integrated perspective."** The second question is addressed in the following comment.

L315: Change "our" to "the". Do you mean the temporally interpolated representation in CARRA?

Response/Modification (L327f): We rephrased: **"Since we lack real observations, we declare the spatio-temporally interpolated AR representation in CARRA as the truth."**

L335: Be more precise about what you want to say with "location and horizontal patterns agree quite well".

Response/Modification (L350): We rephrased: **"In our comparison of CARRA with ERA5, the location of the ARs and the horizontal IVT patterns match quite well (not shown)."**

L340: "(…) before dedicated observations." I don't get the coherence in this sentence

Response/Modification: We have deleted this part.

L341: I still find it confusing that six dropsondes are used here. This and also the motivation for using equidistant dropsondes should be clarified.

Response/Modification (L355f): We updated Fig. 7 and now included seven sondes for better consistency. Furthermore, in this part we are not interested in any sector specifications and only consider the overall moisture transport variability inside the AR. For this reason, we reformulated: **"When the observational focus is on the IVT variability, in general, not on sector-based characteristics, we can simply place the sondes equidistantly."**

L350 and 352: Before, you talked about "continuous" in a different context. Maybe better to specify this here as 1-min resolution profiles, if that is the case.

Response/Modification: In **L366**, we added a reference to the section to make clear, that *continuous* here also means our time-evolving flight representation:

"[…] by comparing their TIVT values to a control case which is based on the continuous representation of the AR cross-sections along the flight (Sect. 2.3)."

We also updated our definition in **L248f**: **"This spatio-temporally interpolated representation of meteorological values and AR characteristics along the flight will from now on be referred to as "continuous AR representation".**

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L358f: What is the maximum spacing recommended for mid-latitudes? Would be good to know. See also comment referring to your conclusion.

Response/Modification (L390f):*:* They did not have a clear maximum spacing recommendation. However, their mean spacing was about 80 km, which we now explicitly refer to in the final statement as: **"[…], which is less than mean sonde spacings of 80 km as conducted for mid-latitude ARs in Ralph et al. (2017)."**

L380: Revise "(…) dries with height. The height decreasing moisture (…)". Actually moisture decreases with altitude due to the decreasing temperatures. Doesn't a drying imply a temporal change?

Response/Modification (L395f): We rephrased: **"[..] while moisture decreases. The decrease of moisture with altitude leads to a decline of moisture transport."**

L388: This sentence implies that a more homogeneous distribution at upper levels implies a weaker wind intensification with height? Does that make sense?

Response/Modification (L403ff): We simplified the phrasing to: **"Above the local wind maximum, the increase of wind speed with height is less than in sub-tropic/mid-latitude cases. Ralph et al. (2005) and Cobb et al. (2021) report on a stronger increase with height due to a more intense upper level jet."**

L425: Although these terminologies are established and I understand that the fluctuations need to be coherent, I do not get why transport by the mean quantities is called non-coherent?
You should comment about whether the variability in CARRA might still be lower than in observations and thus is underestimating this effect of fluctuations. I guess it would need a spectral analysis to see what scales are dominating the covariance and compare this for observations and simulations?

Response/Modification (L444): We have included a remark to make sure for the reader that we cannot fully answer this question with a reanalysis where we lack observations:
"Assuming that CARRA resolves the scales of dominant fluctuations, […]"

L456: Wouldn't it be better to talk about "fluctuations" instead of "patterns"

Response/Modification: Since the fluctuations are spatially clustered, we find pattern more appropriate.

L475: What are "calm air masses"? Now it is more confusing to understand Fig. 12 as it is different to Figure 5 regarding the axis orientation. In addition, it is confusing me where the post frontal cold sector actually is (see comment to Fig.5).

Response/Modification (L493): See comment for Fig. 5, they are in the same axis orientation. All cross-sections are shown in flight direction. We rephrased: **"The steep post-frontal IVT decline in AR2 and AR7 results from weak low-level winds west of the AR."**

L488: What means "are suggesting"?

Response/Modification: We found "to suggest" more appropriate as "to indicate", since we do not purely trust the TIVT-based explanations of divergence/convergence. We checked the sentences for correct grammar.

L489f: What means "decided to use"?

Response/Modification (L506f): Changed to: **"Therefore, we choose the regression approach [..] to diagnose"**

L499: I do not understand what you mean with "most crucial"? Do you mean that the strongest divergence occurs in the cold sector? Be specific about where.
Response/Modification (L516): We rephrased: ***"*The moisture transport divergence is strongest in the post-frontal sector with both signs*."***

L503: "locate at" change to "are located at". Be specific about "the heights"
Response/Modification: We verified that we actually mean that they are NOT located at the dominant heights of wind and moisture, as moisture is highest in the marine boundary layer and winds peak in the low-level jet and the upper level jet. The dominant heights of wind and moisture have been described already, so that we here only describe the vertical characteristics of the divergence components.

L507: Why "dominates" and where?
Response/Modification (L524f): Our statement was misleading so that we rephrased: **"The vertically integrated moisture transport convergence (divergence) is highest in the cold post-frontal (warm pre-frontal) sector of AR3 (Fig. 13), while the post-frontal sector shows the strongest variations with height."**

L524f: "When..." Consider revising the complicated sentence.
Response/Modification (L542f): We rephrased: **"Comparing our synthetic results with the mid-latitude based airborne study of Norris et al. (2020), which used real dropsondes, we see the strength of real sondes in their high vertical resolution."**

L526-528: You mean the vertical resolution of the model? What about missing variability in the model?
Response/Modification (L543f): Yes, we clarified: **"Real dropsondes provide much larger vertical variability than CARRA."**

L540: "as the AR spread out" – what does that mean?
Response/Modification (L558f): We rephrased: **"However, the low-level mass convergence below 800 hPa [..] is often superimposed by mid- and upper-level mass divergence [...], where the AR widens causing directional divergence. "**

L549: Please specify "frontal characteristics of CONV"
Response/Modification (L568ff): We rephrased: **"In turn, the fact that CONV is found to be divergent in the prefrontal sector and core in arctic ARs contradicts the findings of Guan et al. (2020), who emphasised a dominant convergence of mass in and ahead of the AR-embedded front for mid-latitude ARs."**

L585: Remind the reader what the "spatially continuous representation" is by adding the profile distance and temporal resolution.
Response/Modification (L602ff): We added spatially explicitly since we were not seeking for temporal interpolation at this time. For better clarification, we rephrased: "**To quantify the deviations in IVT divergence due to non-instantaneous observations, we contrast the spatially continuous representation, which is the spatially interpolated CARRA data at the aircraft location for each point, in two temporal perspectives. This is done by establishing an instantaneous reference. The instantaneous reference is based on the spatially continuous airborne representation, but only for the CARRA output at the central hour of the flight, without interpolation in time. This can be thought of as a continuously sampling and infinitely fast aircraft, so we refer to it as the optimum airborne representation. We contrast the sector-based ∇IVT of this reference with the**

one of the non-instantaneous continuous representation defined in Sect. 2.3 and analysed in the previous sections, which takes the flight time into account. "

L660: I wonder about the factor of 2 in the range of the spacing of the dropsondes. I would have expected you can be more precise. Maybe add the respective error ranges. Compare to the midlatitude value (see comment above).
Response/Modification (L684): We give an updated recommendation of 100 +/- 20 km.

L661: What does "rely on steepness" mean in the context of flight planning?
Response/Modification (L685f): We found the "steepness" as to vague. With a reference to flight planning, we rephrased: **"The planning of sonde releases should thus rely on the forecasted gradients of IVT along the cross-sections.**

L666: Delete "height and less at other height" and make clear if 0.5 is the highest mean correlation coefficient.
Response/Modification (L691f): We rephrased: *"***Moisture and wind in arctic ARs are only moderately correlated along the flight transects, with a maximum mean correlation of 0.5 at about 850 hPa height, but much less at other heights."**

L670: What does "collocated sampling of (..) not of first priority" mean? Is that connected to the last sentence in L676. Could you comment on how supplementary observations would help?
Response/Modification (L695f): We rephrased: **"We draw the conclusion that collocated sampling of wind and moisture is not a priority."** At the end of the bullet point, we give information on how supplementary observations may help to estimate IVT variability. Furthermore, when listing the implications for future flight planning in **L739f**, we added: **"In addition to the sondes, complementary measurements of moisture should be prioritised due to its higher variability, and its advection dominating moisture transport divergence."**

L676ff: Avoid "is expected" and write what you have done. What are "Arctic AR edges? Are there more than one "post frontal sector"? Be specific about the dominating process and the overall contribution of the individual sectors to the moisture budget.
Response/Modification (L700ff): We rephrased this bullet point for more specific clarification: **"Contrasting the ingoing and outgoing *TIVT* of the AR flight corridor using the two cross-sections suggests an overall divergence in *IVT*. However, the ARs show different characteristics of IVT divergence (∇IVT) in specific sectors across the AR-embedded cold front, especially when we decompose ∇IVT into moisture advection (ADV) and mass convergence (CONV). The advection term contributes most to the entire moisture transport divergence across the AR, especially in the pre- and post-frontal sectors (Fig. 15). The pre-frontal AR sector contributes via moist advection, while the post-frontal sector generally shows dry advection. Across the front, the total contribution of IVT divergence to the moisture budget is up to +1 mm h^{-1} (pre-frontal moisture advection) to -2 mm h^{-1} (post-frontal dry advection). This is slightly less than the magnitudes in mid-latitude ARs. However, in contrast to mid-latitude ARs, mass convergence is much less dominant in the arctic ARs apart from the post-frontal sector. Although the convergence of mass is generally dominant below 850 hPa, upper-level divergence often superimposes it. The advection term dominates at levels higher than 850 hPa. For the post-frontal sector, this is mostly dry advection of cold airmasses west of the AR."**

L687ff: I think I still do not understand this result completely. What are potential explanations for the large differences between instantaneous and non-instantaneous for values Arctic AR? If you look at the total over all sectors - what is the difference? Does that relate to the northern location of the sections at the ice edge? How do these findings affect planning of flights (L630)? What can you learn from observations about IVT divergence?

Response/Modification (L718ff): We put more focus on describing the overall differences between both samplings (which are basically the weaker gradients across the AR) and explain the reasons more thoroughly as: **"The AR instationarity over flight time, including a displacement of the AR not necessarily along the moisture transport direction, deteriorates the results more than undersampling and leads to an underestimation of the sector-based gradients in moisture transport divergence. In fact, the pre-frontal moisture advection and the post-frontal sector divergence (from *ADV* and *CONV*) are stronger than assumed by sondes. Sonde-based values deviate the most in the post-frontal cold sector, where the AR has stronger gradients in moisture and winds than in the pre-frontal sector. The eastward displacement of the AR during flight deteriorates the post-frontal wind and moisture conditions seen from the sondes. Over flight time, the northern cross-section becomes drier due to dry intrusions of air masses from west of the AR. The emerging negative meridional moisture gradient between both cross-sections, that is then seen by the sondes, suggests a meridional advection of moisture that partially compensates the actual dry advection. This misrepresents sonde-based ADV and frequently causes deviations higher than 50% of the actual values."**
How this affects flight planning is further described in **L733ff**.

L709: "Still feasible" in what sense?

Response/Modification (L738f): We have rephrased: **"The optimal and practically realisable strategy is to have collocated flights by two aircraft, with both cross-sections not far apart and sampled simultaneously."**