Response to the comments from Anonymous Referee 1 for the submitted ACP paper: ´Dorff, H. et al. (2024): Moisture Budget Estimates Derived from Airborne Observations in an Arctic Atmospheric River During its Dissipation

Prefaces:

We thank the ACP associating editor, Michael Tjernström, as well as the Anonymous Referee #1, for the enlightening review. Please find our responses (in standard font) to the remarks from the Anonymous Referee #1 (in *italics*) below. Modifications in the manuscript are **bold.**

This response is structured in such a way that major revisions on the most relevant sections (introduction/conclusions) are distinguishable from each other, before chronologically addressing the minor comments.

We reserve the right to apply slight 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:

The authors quantify and discuss the contributions of evaporation, precipitation and transport to local changes in integrated water vapour in an Arctic atmospheric river using airborne observations. Understanding moisture budgets in such extreme advection events is an interesting topic, and the manuscript is technically sound.

Response: First of all, we want to expressly thank you for the very detailed and well-specified feedback and appreciating our work. We are certainly confident that the consideration of your remarks enables a significant improvement of the manuscript. Addressing your remarks helps us to crystalize the scientific relevance of our study in better understanding the role of individual AR events on the Arctic water cycle at the intersection of Arctic ocean and atmosphere.

Introduction:

What I am missing is to understand why the authors did what they did, […]. The authors define their research goals in the introduction, but do not really motivate them based on identified knowledge gaps.

Response: With respect to the Arctic amplification, the amount and role of water vapour in the Arctic atmosphere is crucial. Water vapour is a key quantity in steering the Arctic radiative equilibrium via the water vapor triple effect (warming caused by condensation, the greenhouse effect of water vapor, and the mostly warming effect due to clouds). Therefore, the investigation of the atmospheric water (vapor) cycle in the Arctic is fundamental and ARs have been identified as the major contributor of water vapour in the Arctic (e.g. Nash et al. 2018).

In the initial paragraphs, we introduce the roles of moisture transport and ARs on Arctic climate and weather dynamics. However, despite the crucial role of ARs on these dynamics, significant knowledge gaps remain regarding the detailed mechanisms driving AR moisture transport and its interaction with surrounding Arctic air masses in the light of the Arctic atmospheric water cycle.

Previous studies on moisture processes in Arctic ARs have primarily relied on simulations, such as climate model data and NWPs (e.g. Bresson et al., 2020; Kolbe et al., 2023), reanalyses (e.g. Nash et al., 2019; Lauer et al., 2023), and coarse observational networks (Nygard et al., 2020). All of them do not adequately capture the fine-scale processes occurring within ARs in the Arctic. Few studies have utilized in-situ observations, focusing on high-resolution observations of moisture budget components, mainly because these data have been lacking. The absence of these observations has hindered research aimed at characterising the evolution of moisture processes and quantifying their specific contributions during individual AR lifecycle phases.

This limitation has restricted our understanding of how AR moisture properties evolve as they travel over complex Arctic environments, particularly regarding their influence on the Arctic water cycle, sea ice dynamics and regional precipitation patterns. For example, discrepancies between modelled and observed precipitation associated with Arctic ARs suggest that our current understanding of these phenomena may be incomplete (Vázquez et al., 2018; Viceto et al., 2022).

Therefore, we now emphasize more explicitly the need for observational studies as they provide empirical data that can help constrain the representation of Arctic ARs in both reanalyses and climate models. In this regard, we consider our aircraft-based observational study a valuable contribution to the AR research community, particularly for the Arctic. Moreover, comparing observations with model-based results illuminates various strengths and weaknesses of both frameworks. Thus, we advocate for such synergies to be conducted as often as possible to better align with the realities of nature.

Modifications: To make our above-mentioned argumentation more explicit, we invested fundamental effort in improving the motivation of our work with more emphasis on the importance of observational reference data, better highlighting the existing knowledge gaps, and the scientific framing in the broader picture of the relevance of water vapour in the Arctic region by ARs. We revised the introduction very thoroughly at many places for these aspects and evaluated where to improve our expressions for conciseness and improved logical flow. Here, we just give some examples that consider our above-mentioned explanations and which we now inserted in the manuscript:

- **(Line 26ff): "Arctic ARs are a key driver of the atmospheric water cycle in the Arctic. Nash et al. (2018) […]. Arctic climate simulations by Kolbe et al. (2023) suggest that enhanced poleward moisture transport in a future warmer climate will likely be almost entirely driven by ARs. Zhang et al. (2023) report that the rising frequency of Arctic ARs intensifies the sea ice losses. However, the response of ARs to Arctic sea ice loss remains a topic on ongoing debate (Ma et al., 2021). These discussions highlight the need to elucidate driving the development of ARs and their interaction with the surrounding cold and dry Arctic air masses and sea surface types."**
- **(Line 44ff): "Despite the role of ARs in weather and climate dynamics and in moist air mass transformations, significant knowledge gaps remain in quantifying the specific physical mechanisms induced by the poleward moisture transport associated with ARs. This includes understanding the extent to which moist air mass transformations in ARs affect the Arctic atmospheric water cycle. To elucidate the transformation processes of moisture in the Arctic ARs, we need to quantify the specific moisture budget components."**
- **(Line 55ff): "Previous studies on moisture processes in Arctic ARs have primarily relied on simulations (e.g.; Bresson et al., 2022) and reanalyses (e.g. Nash et al., 2018; Lauer et al., 2023; Dorff et al., 2024), or are limited to individual measurement stations (Viceto et al., 2022) and coarse observational networks (Nygard et al., 2020). We lack studies that provide a direct observational reference to validate models and reanalyses regarding their capabilities and limitations in representing moist air transformations in Arctic ARs."**

On the explicit motivation of our research goals:

Response: In our preprint version, we intended to introduce each research question in a specific paragraph, which we did not achieve sufficiently. We acknowledge that the logical flow in these paragraphs needed improvement. Additionally, we now refrain from our initial approach of consistently stating each research goal/question at the end of its respective paragraph. Consequently, we restructured the relevant paragraphs to more clearly address the existing gaps in knowledge and research concerning moisture budget components in Arctic ARs. These modifications are outlined as follows for each research goal (G1-G3):

G1: In the preceding paragraph, we emphasized the strengths of research aircraft based on previous case studies and the difficulties when auxiliary measurement platforms are necessary. Now, we restructured the paragraph of research goal G1 in stating the research goal right at the beginning of the paragraph after we have presented airborne mid-latitude cases and better highlight the added value of airborne observations. This is followed by a specification of the HALO-(AC)³ campaign. **Modification (L79ff): "Therefore, the first research goal of this study is to derive all moisture budget components in Arctic ARs from a research aircraft (G1), addressing the existing gap in moisture observations in Arctic ARs. We focus on the HALO-(AC)³ aircraft campaign conducted in March and April 2022 (Wendisch et al., 2024), which observed air mass transformations in meridional atmospheric transports over both open ocean and marginal to closed sea ice regions of the North Atlantic and Arctic Ocean. The first campaign week was characterised by a series of ARs propagating across the North Atlantic towards the Arctic (Walbröl et al, 2024). Special flight patterns were designed to sample enclosed AR subregions."**

G2: By rearranging the statements in introducing the second research goal, we aim to sufficiently improve the logical flow in the corresponding paragraph and the motivation for investigating the temporal evolution. **Modification (L85ff): "When ARs reach the Arctic, they are typically in the dissipation phase of their life cycle (Guan et al., 2019) To understand the moist air transformations in Arctic ARs, monitoring of moisture characteristics and processes throughout this dissipation is essential. However, the spatio-temporal tracking of AR characteristics has mainly relied on simulations (Guan et al., 2019; Kirbus et al., 2023). We use the airborne AR moisture budget components to examine how the moisture budget components evolve during the dissipation phase of the AR, which comprises the second goal of our study (G2). During HALO—(AC)³, we observed an intense AR event sampled by HALO over two consecutive days (March 15 and 16, 2022). Over this period, the AR showed a significant decrease in intensity (quantified by IVT) and dissipated considerably."**

G3: We also restructured the consecutive paragraph describing RQ3 and applied some slight changes, resulting in the following paragraph version **(Modification L92ff)**: **"The observation-based budget components are tainted with uncertainties. Norris et al. (2020) showed that the uncertainties cannot be neglected; they must be quantified to interpret the budget components and the emerging residuals. Furthermore, the airborne moisture budget estimates refer to rather large areas sampled by a single curtain along the flight path. Norris et al. (2020) and Dorff et al. (2024) conclude that the non-stationarity of ARs during the flight leads to significant deviations in the budget components. Still, they examined the spatial representativeness to a lesser extent. Therefore, our third research goal is to assess how accurate and representative the airborne budget components are for the entire AR flight corridor (G3). This assessment of the representativeness of the airborne values for entire AR sectors further enhances the uncertainty analysis of previous studies. To explain potential effects that deteriorate aircraft-based values of moisture budget components, we conduct a model-observation comparison and utilize the model grid data to mimic airborne observations."**

Conclusions:

Therefore, when those research questions are answered later in the manuscript, is was not obvious to me how the answers fit into and extend or improve the big-picture understanding.

Response: In the following, we will briefly summarise the improvements in understanding Arctic ARs by our airborne observations within a broader context. A major achievement of this study is the observational demonstration of the feasibility in deriving the moisture budget components for extended AR sectors.

We have shown that it is possible to complement and evaluate model-based analyses of the AR moisture budget using a single research aircraft. This is why we put considerable effort into describing all technical approaches in detail, to provide a basic framework and to promote future flight strategies— by either repeating our approaches for new cases or by improving methods based on our results and implications found. With our residuals, we provide a quantitative estimate of the reliability of our results, even though models appear to do a very good job of representing AR conditions in the Arctic. Such observations are essential for validating the capabilities and limitations of the models in describing moisture processes in Arctic ARs. Furthermore, complementing observational studies with models, as done in this research, is also enlightening for understanding the nature of phenomena beyond the observational snapshot. Therefore, future field campaigns— not only airborne campaigns— should always consider a model-confrontation to assess the representation from both datasets.

Our observations provide new insights at an unprecedent spatial resolution. This is particularly true for the highly accurate profiling of moisture transport using dropsondes. No satellites or other measurement platform are capable to measure wind- and thermodynamic profiles as effectively as frequent dropsonde releases, which are not limited to single locations and can span the defined AR sectors. However, what the dropsondes cannot provide is a continuous along-track representation of moisture transport, leading to subsampling errors, as we have evaluated in our study.

While maintaining the overarching structure of the conclusions, we have made significant revisions to specific paragraphs. Before discussing the achievements of the respective research goals (G1-G3), we modified the first paragraph to briefly summarise the role of this study and to place it into the current state of research. Furthermore, we made additional statements more concise. **Modifications (L628ff): "This study provides comprehensive observational reference data that complements reanalyses and climate models to characterise the evolution of the moisture budget components in an Arctic atmospheric river (AR). The High Altitude and Long-Range research aircraft (HALO) sampled an intense Arctic AR, traversing the Greenland and the Norwegian Seas toward the Arctic sea ice. From the airborne measurements, we developed and applied methods to derive all major atmospheric moisture budget components in an Arctic AR, and investigated four pre-frontal sectors (S1-S4) throughout the dissipation of the AR. […]"**

When summarising the achievements of our three research goals, we have now added overarching conclusions to better contextualise our work within the broader research and understanding on moisture processes in Arctic ARs. In addition to some minor changes not specified here, we show the modifications for each summarised research goal below:

G1: We have shortened a bit our explanations of the final methods in the conclusions, as they were too detailed. Instead, we now emphasize that the success of an airborne moisture budget closure facilitates further model-observation comparisons, which are essential for constraining model representations in the Arctic. **Modification (L634ff): "We show the feasibility of deriving the budget components using measurements from instruments on a single aircraft. Dropsondes released from zigzag flight patterns provide highly accurate profiling of moisture and wind at inflow and outflow cross-sections, with near-surface**

dropsonde data used for estimating evaporation. The dropsondes enable the calculation of moisture transport and thus *IVT*. Using training data from ERA5, a regression retrieval diagnoses *IWV* from brightness temperatures (TBs) measured by 25 microwave channels of an airborne radiometer. The results show good agreement with dropsonde data (RMSE < 0.5 kgm^{-2}). The computationally efficient regression retrieval can be adapted to different training data various regions; however, it is unsuitable for sea ice-covered areas. Precipitation rates were estimated from nadir Ka-band radar reflectivities. To address uncertainties, we applied a set of Z-R/ Z-S relationships. Despite the high latitude and season, both rain and snow coexist in the AR. Omnipresent melting layers require attenuation estimates to correct the precipitation rates.

Although all airborne moisture budget components involve significant uncertainties, these remain smaller than the actual component magnitudes. This observational success, based on our zigzag flight strategy, facilitates future mission planning for airborne budget closure flights aimed at much-needed model-observation comparisons in the Arctic."

G2: We have restructured the second bullet point concerning G2 to enhance the logical flow. We now first highlight the characteristics specific for our AR case and then conclude how these insights contribute to our understanding of Arctic ARs in general. **Modifications:** We have rephrased the respective bullet point as follows **(L648ff):**

"Despite the AR dissipation due to *IVT* decay, the absolute magnitude of the moisture budget components remains relatively constant in the pre-frontal sectors. Within the Arctic AR, the components contribute to the moisture budget in a range of ±1 mm h^{-1}, slightly lower than that found in mid-latitude ARs (Guan et al., 2020). The pre-frontal sectors show a transition from a local drying to moistening during dissipation. On the first day, a divergence due to the pressure field causes mass-divergent drying up to −0.53 ± 0.07mm h^{-1} (S2), but heterogeneous precipitation and deep clouds resist the moisture transport divergence. On the second day, the convergence of moisture transport, primarily driven by moisture advection (0.59 ± 0.14 mm h^{-1}, S3), leads to atmospheric moistening. For both days, the dropsondes indicate that the marine boundary layer maintains moisture with q > 4 g kg^{-1}, with mid-levels more influenced by advection.
This case study highlights that local changes in IWV within the Arctic AR are primarily driven by moisture transport divergence via advection. This connection aligns with prior studies of pre-frontal moisture budget components in mid-latitude ARs (Cobb et al., 2021a; Guan et al., 2020) and emphasises the role of moisture transport in shaping regional Arctic moisture patterns (Nygård et al., 2020). Notably, the drying observed in the pre-frontal sector contrasts with patterns seen in mid-latitudes, where this sector is typically associated with moisture advection. The moist air masses within the Arctic AR exhibit weak surface interaction concerning precipitation and evaporation. However, the high spatial variability of precipitation complicates quantification in Arctic ARs, necessitating future research. For the Arctic atmospheric water cycle, this case study suggests that when AR moisture transport occurs over the Arctic ocean, moisture is predominantly distributed in the atmosphere. Precipitation is marginal outside of the AR core, particularly in the absence of strong moisture transport convergence or orographic forcing, leading to reduced impacts on the sea-ice properties. The AR core is characterised more by a clustering of cellular plumes of precipitation than by a compact precipitation band."

G3: We have revised the third bullet point, resulting in updated formulations that make our statements more explicit and concise. In accordance with RC2, we also highlight that the conclusions apply for all pre-frontal sectors observed (not only S1). Additionally, we now emphasize the impact of spatial variability on budget closure purposes. However, we chose not to detail the further implications for future flight mission planning and emerging research questions at this point. Instead, we use the last paragraphs to outline these implications. Consequently, the last bullet point corresponding to the achievements of G3 was reformulated as follows **(Modification**, **L669ff)**: **"The closure of the moisture budget using the mean airborne budget components results in significant residuals for all sectors, with magnitudes of 0-1 mm h^{-1}, comparable to dominant budget components. Once uncertainties in the components are considered, the moisture budget can be closed for all sectors except S2. In comparison to model-based budget components mimicked along the flight, we find that the airborne values are realistic, consistently reflecting either drying or moistening throughout all sectors (not all shown) for both ICON-2km and ERA5. We note a sensitivity of ∇IVT values to the sonde spacing. However, in all sectors, sonde-based ∇IVT differs by less than 25 % from that of mimicked continuous sampling. The observed precipitation rates are in better agreement with ICON-2km than with ERA5, both in terms of mean values and variability across all sectors. While the airborne observations offer high spatial resolution for along-track precipitation and vertical variability of the moisture transport divergence, their spatial representativeness across the entire sector is limited. ICON-2km indicates that several precipitation fields tend to be located outside the internal flight legs. Additionally, even with an idealised continuous IVT sounding along the flight track, the subscale variability between the two cross-section legs remains significant (especially for $\nabla \cdot IVT$ in S1 and S2). This subscale variability underscores the limitations of the flight pattern, which hampers the closure of the airborne moisture budget when the meridional distance between cross-section legs is too great."**

We use the following updated paragraphs to elaborate on the implications of our study and how our achievements of the research goals contribute to understanding of AR moisture processes in the Arctic, especially regarding the limitations and capabilities for both airborne observations and model data. Still, we have to emphasize that our results rely on a single-case study, highlighting the need for additional cases to substantiate our results. Furthermore, we advocate for more airborne investigations of ARs by outlining implications and perspectives for future measurement campaigns and flight strategies that arise from our results.

We have added a paragraph, focusing on new knowledge with respect to constraining AR model representations. **Modification (L683ff): "This study is limited to a single AR event. Nonetheless, our model-observation comparison already reveals both the limitations and strengths of each perspective. The observations provide insights in the AR moisture processes in an unprecedented spatial resolution. For example, the sonde-based moisture transport convergence at LLJ heights, which is poorly represented by the models, should be investigated across different AR events, as Dorff et al. (2024) emphasize high case-to-case variability for Arctic ARs based on reanalyses. Such investigations will help substantiate the robustness of our findings regarding model-based misrepresentation of LLJ dynamics in Arctic ARs. This also applies to the significant precipitation variability observed by radar, which is below the effective resolution of the model data for all sectors."**

Furthermore, we restructured the paragraph concerning the importance of achieving a closure of the moisture budget by airborne observations, and emphasize the benchmarking of reliability that can be obtained from the residuals and model comparison. **Modification (L690ff): "The closure of the moisture budget using HALO builds upon recent studies on airborne moisture budget components in mid-latitude ARs (e.g. Neiman et al., 2014; Norris et al., 2020). The uncertainty ranges of our residuals affirm the feasibility of the airborne moisture budget closure. Like Norris et al. (2020), we emphasise the importance of quantifying uncertainties for a robust observational moisture budget closure. From their values, we see a good agreement between our airborne budget components and the airborne-mimicked model representation, which underscores the reliability of our**

observational estimates. This feasibility provides significant potential for future airborne research on Arctic AR moisture budget components."

In addition, we restructured our discussion on the limits and potential improvements in future studies, by merging them in a corresponding paragraph. **Modification (L696ff): "However, our airborne results are partially limited by reduced spatial representativeness, as significant subscale spatial variability is not captured by the flight curtain. Future flight patterns should retain the long cross-sections across the AR while reducing the distance between them. Shortening the meridional extent and flight duration may lessen the impact of nonstationarity, leading to improved divergence estimates. Dorff et al. (2024) indicate that flight duration is more critical than sonde spacing for the misrepresentation of ∇IVT . This facilitates the verification of our observations in future airborne studies."**

The last paragraphs forming the outlook of our study underwent some changes in wording, with a stronger focus on the potential for further research using HALO-(AC)^3. We made minor changes in wording that we do not specify in this response for the sake of brevity.

Minor suggestions:

The abstract would benefit from 1-2 sentences placing the research into a wider context (see above).
Response/Modification: We have added **(L1)**: **"Atmospheric Rivers (ARs) are essential for the Arctic water cycle, but observations quantifying the moisture processes in individual Arctic ARs are sparse."**

Line 82: I suggest deleting "pioneering" and "of this study"
Response/Modification: Done.

Line 120 ff: choose consistent tense for describing data processing
Response/Modification: The data processing is now consistently described in past tense.

Line 131: The sentence on the GTS could be misleading, as the GTS only collects and provides observations, whereas data assimilation happens at different modelling centers.
Response/Modification: We have rephrased this as follows **(L133f)**: **"A large part of the sonde measurements were transferred to the Global Telecommunication System (GTS) for inclusion in the model assimilation of operational Numerical Weather Prediction (NWP)."**
Line 137: Is there no difference between zonal and meridional spacing?
Response/Modification: In this region, the spacing is comparable in both zonal and meridional direction. Thus, we added **(L139f)**: **"[…], the ERA5 latitude-longitude grid results in zonal and meridional spacings of about 30 km."**

Line 159: "quite strong" - can you quantify that?
Response/Modification: We intended to refer to the intensity of the ARs in terms of IVT. We compared IVT values to long-term statistics in Walbröl et al. (2024). They show that mean IVT for the ARs sampled by HALO-(AC)³ are frequently above the 75th percentile of mean IVT values for long-term AR statistics (Walbröl et al. 2024; Fig.8). However, we have the impression that including too much detailed information in our study may impair readability and distract from logical flow. Therefore, we have added the following specification **(L161ff): "Walbröl et al. (2024) showed that these ARs were notably strong in terms of IVT for common Arctic ARs."**

Line 176: a large extent of the atmospheric river? Or an area from the AR to Scandinavia?
Response/Modification: We rephrased as follows **(L181f): "θ_e exceeded 285 K over a large area extending from the AR along the 0° meridian to Scandinavia."**

Eq.1: The manuscript finds that transport divergence dominates the budget – is that a characterization of the AR or just stating the fact that the AR is moving (out of the observed box when we see drying through advection)?
Response/Modification: First of all, it is primarily the divergence of moisture mass that contributes to the moisture transport divergence, leading to a drying during the first flight day (RF05), as indicated by the bars in Fig. 13. Nonetheless, we agree that dry advection is significant in S2.

We acknowledge your valid point regarding the AR displacement possibly deteriorating our impression of predominant advection. However, the AR extends over a several thousand kilometers in the meridional direction, while the flight pattern of RF05 (2022-03-15) covers a meridional distance of less than 500 km. Furthermore, at least for the first sector, the flight pattern is oriented in a streamwise direction; first the southern cross-section is conducted, followed by the northern (outflow) cross-section. Thus, the flight pattern aligns with the AR, reducing the risk of the AR moving out of the observation region, which could create a misleading impression of dry advection.

Nonetheless, your point is very important for considering and building upon the reanalysis-based findings in Dorff et al. (2024), where the nonstationarity of the AR (e.g., by displacement of the AR filaments over time) adversely affects airborne results regarding moisture transport divergence. Following the procedure outlined in Dorff et al. (2024), we have thus mimicked the sonde-based moisture transport divergence in the model representation for two time-scenarios: one simulating the aircraft-following representation over the flight duration, and the second idealising an infinitely fast aircraft providing an instantaneous snapshot of the AR.

From this time representation comparison, Figure A1 illustrates the results we refer to in the manuscript for the pre-frontal sector S1. For the airborne-collocated representation (orange dashed line, Fig. A1), we again observe that mass divergence dominates the divergence of moisture transport, as the advection is much weaker throughout the troposphere. However, above the 700 hPa level, there is a considerable amount of dry advection based on the airborne representation.

If, however, the aircraft could provide an idealised instantaneous sampling of the AR, we observe that there would be notably more moisture advection, while the results for mass divergence are less sensitive to the flight duration (this also applies to S2, which is not shown here). This is why, in Sect. 5.2 of the manuscript discussing the plausibility of the airborne moisture transport divergence in terms of spatial representativeness, we now mention the following **(L562ff)**: **"As a second effect, Dorff et al. (2024) emphasize the temporal evolution of the AR, e.g. by AR displacement during flight, causing nonstationarity that represents a relevant source of error for sonde-based estimates of moisture transport divergence. In our case, both models reproduce stronger advection of moisture in the instantaneous view compared to the non-instantaneous observations (not shown). This stronger advection would, in turn, increase the residuals.**

Nonstationarity becomes most effective in deviating the airborne results when there is a high subscale spatial variability. […]"

We decided not to include Fig. A1 in the manuscript for the sake of brevity and because our responses (including the figure) are accessible through the open-discussion program.

Eq. 5: Why is this cd rather than ch? Are two values for two ranges of wind speeds the latest state of research on this? What about the COARE algorithm?
Response/Modifications: We followed the equations and labelling from Rao et al (1981) and Howland et al. (1983), both of which use "d" as an index. We appreciate your suggestion for the COARE algorithm, which is indeed a more elaborate approach to calculating evaporation. We agree that the two discrete values for c_d that we use are a strong simplification, and thus the COARE algorithm should be mentioned in this part of the manuscript. Moreover, we want to point out that the COARE algorithm could enhance the calculation of evaporation.

Nonetheless, in our model-observation intercomparison (as also shown in Fig. 5 of the manuscript), we found that our observation-based bulk evaporation is within a realistic range, with only small deviations to ERA5 (Fig.5) and ICON (not shown). Additionally, this comparison revealed that evaporation plays a minor role as a component of the moisture budget component in the AR, with maximum evaporation below 0.2 mm/h. Therefore, we refrain from adding more complexity in the evaporation calculations, as this would be outside the scope of this manuscript given the minor role evaporation plays in moisture processes in Arctic ARs.

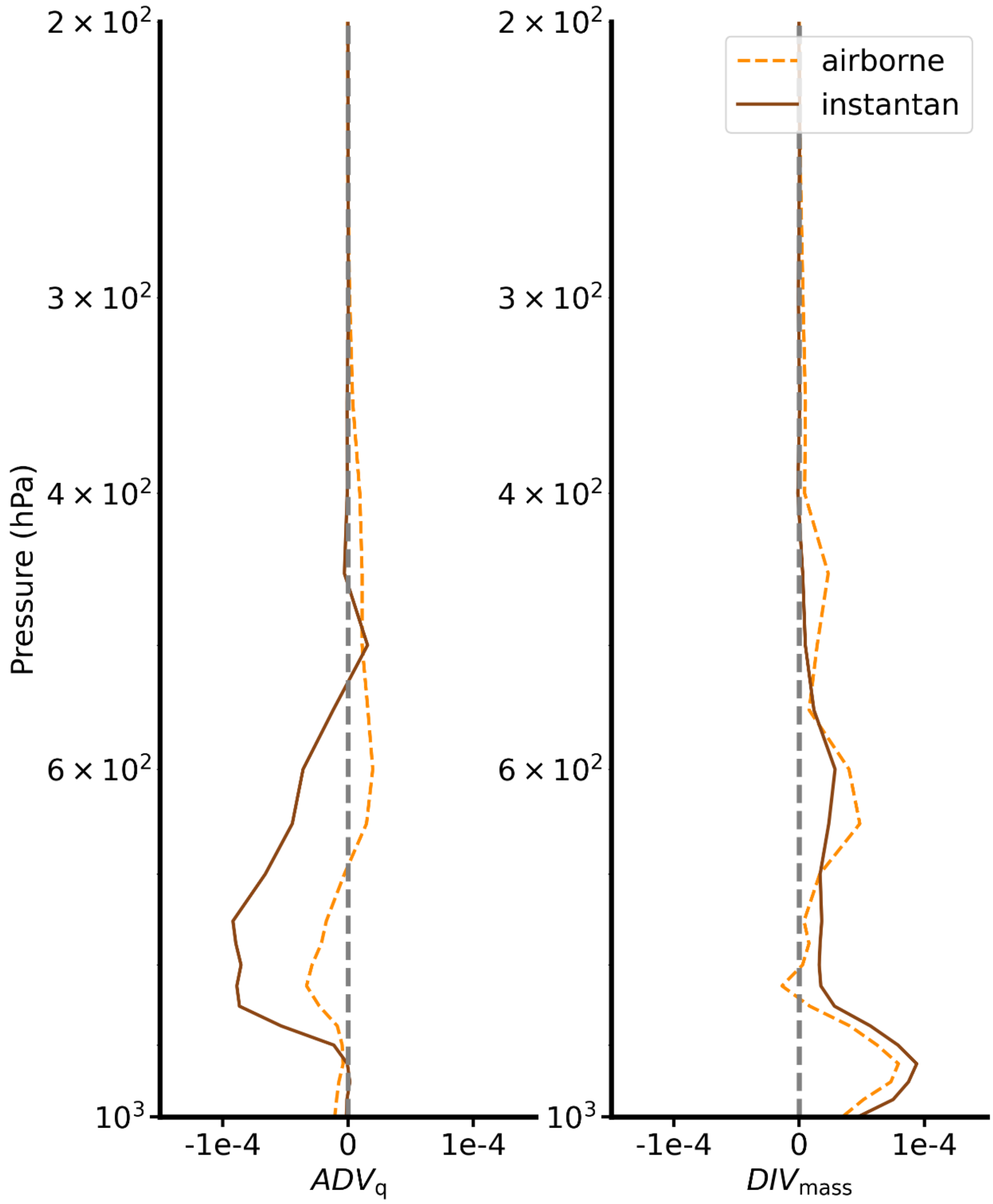

Figure A1: Vertical profiles of ERA5-mimicked sonde-based moisture transport divergence, specified for advection ADV and mass divergence DIV for the first pre-frontal sector S1. The curves represent the ERA5 mimicked sonde-based results for two temporal representation scenarios. The airborne curve (orange-dashed) corresponds to the flight duration, utilizing spatio-temporally interpolated ERA5 data, while the instantaneous representation (brown curves) reflects the centred reanalysis timestep, approximating an infinitely-fast flying aircraft providing profiling simultaneously at all sonde-locations.

To still highlight the more reliable calculations produced by the COARE- algorithm, we inserted the following statements in the manuscript **(L311ff): "Note that Fairall et al. (2003) suggest more detailed calculations of evaporation. However, given the overall agreement of our sonde-based results with model data (Fig. 5), the simplified approach in Eq. 5 appears to be appropriate for Arctic AR with small *E*."**

Line 398 – what is G2?
Response/Modification: We have clarified in **(L409)**: **"(research goal G2, Sect. 1)".**

Figure 9: what processes drive the decay in IWP and IVT? What can we learn from the strong reduction in transport than water vapour? Do you expect this to generalize to other ARs?

Response: The comparison of IWV and IVT tendencies indicates that the reduction in the moisture transport is relatively stronger than that of moisture, as IVT decreases stronger than IWV. However, using these integrated quantities and the individual flight corridors, it is complex to disentangle the specific processes causing the declines in moisture and moisture transport. A closer examination of the vertical profiles of moisture and wind speed provides more insight into the relevant processes causing the different declines. For all sondes along the specific zigzag flight corridors corresponding to S1-S4, Figure A2 shows the average vertical profiles of moisture and wind speed, and of the moisture transport (divided by the gravitational acceleration g). According to these profiles, the dominant factor in decreasing the moisture transport is the predominant wind speed (Fig. A2b), while moisture (specific humidity; Fig. A2a) remains relatively constant over time at heights where moisture transport dominates.

Investigating ERA5-based surface pressure and geopotential charts (not shown), we find that the reason for this reduction in winds, and thus the decrease of the AR, is primarily the decline of the steering low-pressure system with its core at the southeastern tip of Greenland. This synoptic evolution reduces the prevailing pressure gradients over our oceanic region of interest, weakening the winds and thereby lowering IVT. Conversely, the warming effect of the AR increases the water vapour holding capacity from the first to the second flight day; thus, it is not surprising that specific humidity remains on high values.

Given this opposite behaviour of both quantities, we strongly suggest decomposing the moisture transport in its two components (moisture and winds) to better understand the ongoing processes. This also explains why we separate both components of the moisture transport divergence to capture the individual processes.

From our case study, it is rather difficult to generalise this finding to other ARs, as e.g. the reanalysis-based study of several AR events in Dorff et al. (2024) emphasises considerable case-to-case variability. However, we postulate that decays in IVT at this AR phase are predominantly driven by decreasing winds due to the longevity of moisture masses in the Arctic.

Even though we appreciate the details visible from the sonde profiles in Fig. A2, we refrain from including this figure into the manuscript for the sake of brevity and because it is here available in the response form of the open-discussion program. Instead, we added short information to Sect. 4.2. by stating the role of the pressure field for the IVT decay, as described in detail above. **Modification:** We added **(L430f): "Reducing moisture transport (IVT) is primarily driven by decreasing wind speeds with a decay of the LLJ due to decreasing pressure gradients (not shown)."**

Line 555: Why not ICON data, which showed the better match?
Response: We understand the rational for choosing ICON, as it shows a higher variability of IVT. However, we opted for the ERA5-based IVT divergence for simplicity, as it is directly accessible as model output. For the ICON-2km grid, IVT divergence is not provided and must be calculated individually, which is more complex due to the grid structure. Therefore, we verified that ICON-2km IVT, when regridded to a comparable spatial resolution of ERA5, generally agrees well with ERA5. If this is the case, we can anticipate very similar IVT divergence between both simulations, at least in terms of large-scale patterns. In particular, the dipole structure of IVT divergence is spatially much larger than the effective resolution of ICON and ERA5. An unresolved sub-grid variability of ERA5 IVT divergence, which is not visible in Figure 15, should therefore not significantly affect our conclusions regarding the dipole structure within the AR flight corridor. **Modification:** We inserted the following short note **(L568ff): "To further examine the spatial variability of IVT divergence within the AR flight corridor, we examine the ERA5 moisture transport divergence field product, which is sufficient to capture the internal large-scale variability that may be missed by the airborne measurements."**

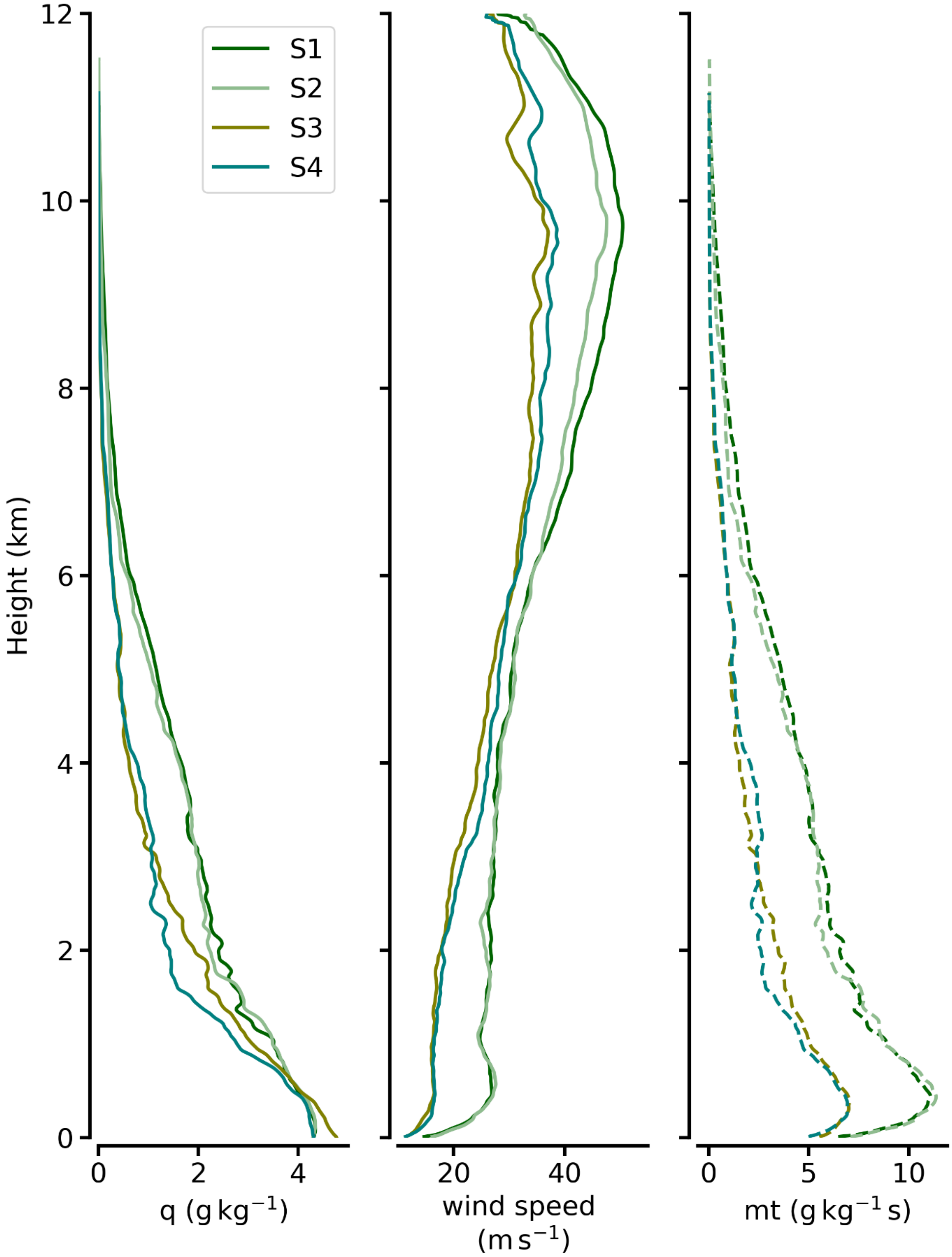

Figure A2: Sonde-based vertical profiles of specific humidity q (left), horizontal wind speed (middle), moisture transport in (right), averaged for all sondes within the respective flight corridor belonging to S1 to S4. Note that the moisture transport is divided by the gravitational acceleration *g*.

Line 592: I did not see where these references show that ERA5 overestimates Arctic precip.

Response: We apologise for this statement. First, the reference to Schyberg et al. (2021) was incorrect, and second, you are right that in Wang et al. (2019), the ERA5-based data does not consistently show a significant overestimation. However, Sect. 3.2.2 of Wang et al. (2019) indicates tendencies of ERA5 overestimation compared to the buoy data. **Modification:** For this reason, we deleted the reference to Schyberg et al. and rephrased to **(L606)**: **"Wang et al. (2019) also found that ERA5 tends to overestimate Arctic Ocean precipitation."**

Line 608: "Our airborne analysis reveals the significance of small-scale precipitation within Arctic ARs as a key finding." I would have summarized that precipitation is small and hard to quantify.

Response/Modification: Your conclusion is very valid and we appreciate to refer to your conclusion by combining both statements as **(L623f)**: **"Our airborne analysis reveals that precipitation within Arctic ARs is hard to quantify. Even if precipitation is rather weak over the ocean, there is considerable small-scale precipitation variability."**

Line 640: see comment on equation 1.

Response/Modification: Given our explanations for the referee's comment on Eq 1, we feel that this point is sufficiently addressed for Line 640. Nonetheless, we checked our statement and had the impression that it is slightly misleading by accidently implying that is only the advection of dry air during RF05, although we referred to moisture transport divergence as a whole. Therefore, we have slightly modified the sentence to **(L660f)**: **"Notably, the drying observed in the pre-frontal sector contrasts with patterns seen in mid-latitudes, where this sector is typically associated with moistening by advection."**