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

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I) Response and Changes to the Comments from Anonymous Referee 1 (AC1)

We thank the ACP associating editor, Geraint Vaughan, as well as the Anonymous Referee #1, for this enlightening review. Please find below our responses (in standard font) to the remarks from the Anonymous Referee #1 (in *italics*), which were given very similarly in the letter of responses uploaded before. The changes/modifications in the manuscript are specified below. Frequently, the major changes consist of rewriting several paragraphs. Citing such paragraphs would partially be too long in this report. In these cases, we only refer to line numbers in the revised manuscript (**bold**). Preprint line numbers of minor comments (grey) now refer to the lines in the revised manuscript (**black, bold**).

Responses to Reviewer 1:

The article is a comprehensive piece of work and presents nice and illustrative figures. I think the presented approach is valid and the content is certainly worth for publication. However, […] the study is not sufficiently motivated and the results are not properly discussed in view of related work. Hence, the novelty in terms of applied methods and results and the added knowledge about Arctic ARs and their observation strategy remains unclear. The presentation quality suffers from a confusing writing style. I recommend major revisions and encourage the authors to carefully rewrite their work to improve the readability of the manuscript.
Response: First of all, we want to expressly thank you for the very detailed and well-specified feedback. We are certainly confident that the consideration of your remarks enables a significant improvement of the manuscript. Your remarks help to transfer our scientific content and knowledge, that is considered as worth publishing, to the reader in a more logical and precise way. Accordingly, in our revision, we focus on improving the readability by more elaborated clarity and structure.

Writing/Grammar

The grammar is a bit awkward and the article misses coherence and logical order within the paragraphs and sentences. The writing of this paper would benefit from a grammatical editing and language check.
Response: We will invest more focus on coherence and the logical order for the paragraphs (individually and in its entirety). We will confirm additional cross-reading of the revised manuscript by either well-experienced or native English speakers.

Terminologies

- *the authors skim over many aspects simultaneously and it is up to the reader to guess potential relationships. Terms like "significant impacts", "pathway of ARs" (in a Lagrangian sense or AR displacement?), "moisture transformation processes", "moisture budget", "precipitation efficiency", "divergence of IVT", "IVT variability", "horizontal corridors", "dynamical and thermodynamical processes", "AR moisture budget components", "AR evolution" (many more examples in the other sections) are not defined or described, which makes it hard to understand the context of this work.*
- *Formulations like "are widely assessed over the mid-latitudes" (L33) or "manifold understanding" (L35) are without substance and should be avoided.*

Response:

- We agree that the introduction, in particular, was overloaded with terms defined/ described little or even not at all. You will find more details in our responses concerning the introduction (see below):

  “significant impacts” → The impact of ARs in the Arctic is now the key topic of the first paragraph and thus specified. **Modification: Term removed**

  “pathway of ARs” → the ambiguous formulation has been modified to specify the long-distance displacement where air mass transformations occur.

  Modification (Line 33f): “Along the long-distance displacement, the AR embedded moist and warm air masses are subject to substantial air mass transformation (You et al.,2022).”

  “moisture transformation processes” → we decided to keep them more or less unspecified. Transformation processes, such as airmasses starting to precipitate, are described above (although not linked to the term “transformation process”). Now we refer to relevant literature (You et al., 2022) and more clearly highlight the relevance of moisture transport to understand air mass transformation processes. Otherwise, we see a risk of distracting the reader more from our major research focus being the moisture transport and its observability if we specify the air mass transformation much more at this early stage.

  “moisture budget”, “precipitation efficiency”, “divergence of IVT” → In order to not confuse the reader by too much details, we erased the term “moisture budget” and focused on the fact that Seager and Henderson et al. (2013) finds the link between moisture transport divergence to local tendencies of moisture amount and how efficiently precipitation is triggered.

  Modification in Manuscript (Line 37f): “Seager and Henderson (2013) point out that the divergence of IVT links the local temporal evolution of moisture amount to the efficiency of precipitation induction.”

  Nonetheless, in our opinion, defining each of the terms once again can be neglected in some cases. In particular, we consider the conceptional definition of divergence (convergence) to be known. A concise definition of the moisture budget follows in Section 2 using Eq. 1.

  “IVT variability”

  We agree that this wording was imprecise. We specified that we mean the spatial variability and added respective findings from Guan et al (2015) describing how spatial IVT variability is composed in atmospheric rivers.

  Modification (Line 39f): Guan and Waliser (2015) considered global ECMWF Interim reanalysis (ERA-Interim, Dee et al., 2011) to specify strong moisture transport gradients that exist along AR cross-sections, perpendicular to the major IVT orientation. Along such lateral cross-sections through the AR center, a bell-shaped IVT distribution, having the strongest moisture transport in the AR core.

  “horizontal corridors”

  We rephrased this.

  Modification in Manuscript (Line 54f): “horizontally extended areas”.

  “AR corridor”

  Later, the term will be defined using Figure 3.

  Modification (Line 193, 198ff).

  “dynamical and thermodynamic processes”,

  We carefully checked the respective phrase, but argued that too much specification here might distract from the key message of this phrase and paragraph, namely the frontal gradients in moisture transport divergence.

  “AR moisture budget components”

  we reformulated the sentence without explicitly mentioning the moisture budget components and solely refer to IVT divergence. By that, the term “AR moisture budget component” is not needed before it is introduced in Sec 2.3.

Modification in Manuscript (Line 47): "Furthermore, the observation of moisture transport requires simultaneous measurements of winds and moisture for the entire troposphere."
"AR evolution"
We specified that we mean the evolution in a temporal sense, meaning the life cycle of an AR and the AR displacement, that cause Eulerian differences over time.
Modification in Manuscript (Line 96f): "Over the flight duration required to enclose an AR corridor, the temporal evolution of the AR (its life cycle and spatial displacement) can affect the sonde-based results significantly."

- **We deleted any formulations like "widely assessed" *(L33)* or "manifold understanding" *(L35)* that impair the argumentation in the introduction.**

Introduction:

The motivation […] remains unclear. I understand that a limited number of dropsondes might affect IVT estimates and […] that Arctic ARs may be not well characterized, but is that all? The authors remain very vague about related work. Although references are given, only rarely a relevant result is described. […] this is needed to understand the motivation of the study.
Response: We suppose that the claims results from our insufficient clear structuring in specifying the motivation and in the identification of the research gaps that emerge from broadly studied airborne observations of ARs (at least in the mid-latitudes). When referring to literature, we mostly miss to pinpoint clear findings relevant for our motivation.
Therefore, we carefully rewrite the introduction to clearly identify research gaps and include the following modifications, addressing several reviewer remarks:

Modifications Introduction:

- We rephrased the first sentence of the manuscript that actually intended to highlight the presence of ARs. Following Referee 2, a *"clear and concise description (definition, shape, evolution, region of occurrence) "*of ARs is now added: **"Atmospheric Rivers (ARs), which are elongated (> 2000 km in length) but narrow (< 1000 km in width) water vapour rich corridors with high moisture transport, occasionally enter the Arctic."**
- The purpose of the first paragraph, which is about the importance of the presence of ARs in the Arctic, is described in more detail. **(Line 24ff)**
- We conducted a more thorough literature review regarding arctic ARs. We stated findings from the literature more precisely. In particular, in the first paragraph that focusses on the importance of ARs in the Arctic on short-term scale, but also at many other places throughout the manuscript. **(not shown here, as distributed throughout entire manuscript)**
- The research focus and overarching motivation of our feasibility study are introduced earlier (4th paragraph, line 56ff). This facilitates the understanding of our conceptual perspective (assess the observability of AR to improve flight campaigns) in the following.
- **Our four research questions are now motivated with respective paragraphs one after another. Each paragraph faces a relevant problem/requirement of airborne moisture transport sounding and refers to knowledge gained from ARs in mid-latitudes. (Line 62ff).**
- *Why should ARs and their observation strategy be different in the Arctic? What is known about Arctic ARs in general and dropsonde-based IVT estimates?* Current studies so far mainly focused on IVT variability within mid-latitude AR centers. For the Arctic, where we do expect less IVT, the sea-ice region is more affected by the outflow region of long-elongated ARs residing over the North Atlantic than by the center of an AR overpassing this region. It can be argued that if IVT and its variability are

supposed to be weaker in the Arctic, then the requirements based on mid-latitude ARs will apply, or even more so, to Arctic ARs. However, the deployment of dropsondes is cost-intensive and should be always optimized in a cost-loss ratio. This should be quantified in such a way: How few dropsondes are sufficient to characterize IVT in Arctic ARs and what is their uncertainty?
Regarding the frontal-specific characteristics of divergence in arctic AR, Guan et al. (2020) and Norris et al. (2020) determined AR frontal differences of moisture transport divergence for mid-latitude ARs. However, we do not know how the divergence/convergence of moisture transport takes place in arctic AR regions. Guan et al. (2023) found that the Arctic is more affected by mature ARs that commonly start to dissipate and by the outflow regions of ARs. Correspondingly, such facts are elaborated more thoroughly in the introduction to better motivate Q3.
Modifications in manuscript: According to the restructuring such points are addressed in the respective paragraphs in Line 62ff and 81ff.

- *How has the problem been addressed (methods)?".* We give more relevant information from the literature (e.g in how the sensitivity to sonde spacing has been assessed already). However, in our opinion, too many details on specific methods to derive IVT divergence should be postponed for the sake of readability. When picturing the remainder of the manuscript, we mentioned more explicitly that an entire section introduces how divergence can be calculated from airborne sonde profiles and how, in detail, it is done in this study.
  Modifications in manuscript (Line 110f): "After introducing our AR cases, Section 2 describes the methods emulating dedicated flight pattern and synthetic soundings, and how we derive moisture transport divergence."
- *How and why were the particular nine cases selected (unclear: L68 "predefined in ERA5", L119ff "picking (…) from catalogue") and why was only the Atlantic region considered? Please explain the purpose of placing the legs at the sea ice edge (L105ff is unclear). Why is only spring considered?* The selection is related to the AR impact on the sea-ice melting when sea-ice reached its maximum extent in spring (paragraph 1). We specify the Arctic ocean as our region of interest due to the fact that the North Atlantic represents one of the most prominent pathways for ARs (Guan et al., 2023) into the Arctic as the moisture transport is undisturbed by any orographic barriers.
  We removed the unprecise information about ERA5 *(Line 68)*. Instead, we revisited the explanation of the case selection in the section introducing the AR cases (Sec 2.2). We added more details (Line 155ff).
  Observation strategy: *How was the simulated observation strategy defined? How do aircraft limitations (flight duration, number of dropsondes) affect the strategy?*
  Response: The different characteristics across the embedded AR front require a large area of interest and the flight duration consists of a couple of hours, in contrast to single circles (being performed to derive divergence in trade-wind regions, Bony and Stevens, 2019). We highlighted that in any case long-range research aircrafts are needed for a strategy to derive IVT divergence in ARs.
  Modifications (Line 54f): "[…], it is necessary to release the sondes at close spacing but over horizontally extended areas above the AR which can only be achieved by long-range research aircraft (Neiman et al., 2014)." We added more information of the width of ARs responsible for the flight duration and the importance of two cross-section legs. In turn, the detailed specifications were added in Sect 2.3 that specifies the reason for our flight strategy (Line 203ff).

Specific remarks in the introduction:

Unusual language:
L31:
Response: we rephrased the sentence:

Modifications in manuscript (Line, 37f): "Seager and Henderson (2013) point out that the divergence of IVT links the local temporal evolution of moisture amount to the efficiency of precipitation induction."

L51 (deteriorate … representation?):
Response: We rephrased the sentence to clarify that too few sondes affect the airborne representation of IVT negatively:
Modification (Line 62f): "Deteriorations in the airborne representation of AR moisture transport variability can result from a limited number of sondes if the sounding spacing becomes too coarse to reflect the spatial variability of IVT."

L57 (monitors transport (…) seen from research aircraft?):
Response/Modifications: As a consequence of our restructuring we deleted this sentence.

In the introduction the reader is distracted by details about CARRA regional reanalyses. I suggest adding more details about CARRA, but in the methods section.
Response: We delete the corresponding sentence and extended the specifications of CARRA in the respective data section:
Modifications (Line 144ff): "Therefore, we further include the C3S Arctic Regional Reanalysis (CARRA). CARRA has a 2.5 km horizontal resolution over the entire domain and is accessible by Schyberg et al. (2021). Driven by lateral boundary conditions from ERA5, CARRA includes more observations and hourly forecasts by the HARMONIE-AROME model (Bengtsson et al., 2017). Køltzow et al. (2022) verified the improved representation of arctic surface-near meteorological conditions in CARRA, with decorrelation lengths of wind speed in better agreement to reference observations than ERA5.

Both reanalyses are provided on pressure levels by the Copernicus Climate Data Store (CDS). While ERA5 contains IVT as output, we calculate IVT in CARRA by the trapezoidal integral of moisture transport along the pressure levels (Tab. 1). In the following, we declare the high spatial resolution representation in CARRA as our idealised background reality of AR features."

Q2 addresses correlations of wind and moisture, which has not been motivated by the introduction. What is (un)known? For understanding Q3, the relevance of IVT divergence needs to be explained more carefully.
Response a): The restructuring of the introduction considered these remarks in the paragraphs. Q2 now has an individual motivation like all other research questions. We motivated more thoroughly the correlations of wind and moisture and their potential interest for the measurement strategies and for different spatial patterns along the AR cross-section. This is done after highlighting the sensitivity to sounding frequency:
Modifications (Line 72f): "**When assessing spatial IVT variability in arctic ARs, it becomes crucial how moisture and wind fields coincide in the AR cross-section or whether they contribute independently to the IVT variability. For instance, in a polar AR case study, Terpstra et al. (2021) identified incoherent patterns of moisture and wind that form the moisture transport patterns but are less aligned than in mid-latitude ARs. The disentanglement of both quantities facilitates flight strategies in the observation of moisture transport divergence in arctic ARs. If the moisture transport variability (and divergence) were e.g. mainly controlled by the moisture field, more investment should be spent on airborne AR moisture representation by supplementary measurements. For this reason, it is important to determine whether moisture and wind are aligned in AR cross-sections and to ascertain: How correlated are moisture and winds in arctic ARs and do coherent patterns contribute significantly to IVT (Q2)?**"

Response b): For Q3, we describe the relevance of IVT divergence more thoroughly with respect to the steering of the local amount of moisture or to precipitation triggering.
Modifications: see again Line 37f and Line 80ff

Section 2 and 3 (structure of the article):

The structure of the method sections is confusing and I suggest that sections 2 and 3 are merged. Section 2.1 (description of dropsonde data that is actually not used) can be deleted. Sections 2.2-2.4 can be summarized in a data and methods section. The TIVT definition (now in Sec. 4) should be moved to the Sec. 2-3.
Response/Modifications: We agree that a merging improves the structure of the manuscript. **We deleted Section 2.1 which is indeed redundant and we come up with a modified structure of Section 2 (merging the original Sect. 2 and 3):**

2 Airborne derivation of moisture transport divergence in arctic ARs
2.1 Reanalysis framework
2.2 Selection of Atmospheric River cases
2.3 Flight pattern and emulated observations
2.3.1 Zig-zag flight tracks observing AR corridors
2.3.2 Synthetic dropsondes
2.4 Sonde-based divergence derivation
2.5 Decomposition in AR frontal sectors

Since this section becomes rather long, we provide some guidance for the reader at the beginning of Section 2, before then coming to the subsections **(Line 128):**
"For this purpose, this section introduces the reanalysis framework we use to investigate a presented selection of arctic ARs. In addition, our airborne flight strategy to derive ∇IVT in arctic ARs is specified and how we emulate the synthetic sondes in the reanalyses. Lastly, we describe the sonde-based derivation of ∇IVT and how we categorise different sectors across the AR front to examine the divergence."

In the following, the responses relevant to the modified Section 2 are specified. All section numbers refer to the modified outline. From Section 2.3 on, this means that the first number of each original major section decreases by one.

Section 2.2

L105ff is unclear. How and why were the particular nine cases selected (unclear: L68 "predefined in ERA5 […] and why was only the Atlantic region considered? Please explain the purpose of placing the legs at the sea ice edge (L105ff is unclear). Why is only spring considered?
Response: We carefully rewrote the first paragraphs of the original Sect 2.2. We moved the definition of IVT to Sect. 2 as it is a basic concept to define ARs. Before, it distracted in Sect. 2.2 when giving details about our individual AR selection criteria. To better explain our selection, we orientate to your question and recapture information given in the introduction as:
Modifications 153ff:
"The transformation of arctic air masses moving over changing surface types (open ocean and sea-ice) along large-scale meridional circulations is part of current research and investigated by research aircraft over the Arctic ocean (Wendisch et al., 2021). For this reason, our study selects ARs causing air masses to overshoot the sea ice edge in

the Arctic ocean. The principle identification of relevant arctic AR events is based on the IVT-based AR detection catalogue by Guan et al. (2022). Among these ARs, we focus on spring season, when maximum sea-ice extent in the Arctic ocean starts to break-up and reacts very prone to the intrusion of warm and moist air (Rostosky and Spreen, 2023). We restrict to conditions and AR events only from last decade, as the arctic climate has witnessed rapid and intense changes over the last decades (Wendisch et al., 2023). Our AR pathways originate from the North Atlantic and Barent Sea that Papritz et al. (2021) spot as dominant regions for arctic moisture intrusions. The selection constrains on ARs whose lateral width is purely situated over open-ocean or sea-ice. This ensures that we do not encounter orographic effects on IVT which are out of the scope of this study. Moreover, airborne observations and sonde releases over land are more complicated to be conducted. Given the criteria above, we selected ARs from nine spring days between 2011 and 2020."

Can you explain the relation of ARs and warm air intrusions (L116)?
Response: Arctic events designated as warm or moist air intrusions can often be classified as atmospheric river, as the intrusions are in conjunction with strong transport of moist airmasses. Due to their subpolar origin, the airmasses are preferably warm compared to predominant arctic conditions. Accordingly, we rephrased:
Modifications (Line 175f): "AR8 originates from Siberia that, according to Komatsu et al. (2018), represents another significant roadway for arctic moisture intrusions favoring ARs."

Regarding CARRA, the authors should "[…] clarify the extent to which km-scale variability of moisture transport can be assessed. The grid spacing (how determined?) and effective resolution of such gridded data are certainly different."
Response: The documentation of CARRA specifies an equidistant 2.5 km grid spacing over the entire model domain. Indeed, the grid spacing differs to the effective resolution of moisture transport. At least, Koltzow et al. (2022) illustrates the significant improvement of the decorrelation length for surface-near wind speed compared to ERA5. According to observations, the correlation decreases rapidly below 0.6 for distances longer than 50 km, roughly the ERA5 resolution in the Arctic. Nonetheless, we are aware that surface near wind is much more affected than upper levels, especially also when over complex terrain.
It is obvious that the resolution of CARRA is certainly different to the effective resolution. If we consider the results from Skamarowk et al. (2014, https://doi.org/10.1175/JAS-D-14-0114.1) designating an effective model resolution of approximately six times the grid spacing, we can still assume that moisture transport can be resolved in the order of several 20 kilometers in CARRA. Using ERA5, we would thus remain in the range of ~100 kilometers and would be in the order of magnitude of envisioned sonde resolution, and cannot make robust statements.
Nevertheless, further investigation of the added value of CARRA in representing ARs is definitely very interesting. For our study, however, we see a risk to overload its content and hope that our study instead motivates further research of ARs using the novel reanalysis CARRA. We come back to this in the conclusions.
In the manuscript, we added:
Modifications (Line 140ff):
Still, Skamarock et al. (2014) emphasise that the effective resolution of processes in simulations is much greater than the model grid spacing. However, if our study aims to assess the sub-grid scale variability of moisture transport between sonde releases from reanalyses, the effective resolution should be of the order of ~ 10 km rather than of ~ 100 km. […] Koltzow et al. (2022) verified the improved representation of CARRA in arctic surface-near meteorological conditions by decorrelation lengths of wind speed in better agreement to reference observations than ERA5."

Why do you use pressure level data only and how might the rather low number of vertical levels influence the results (L374)? What is the separation of the levels in the lower troposphere?

Response: The advantage and our reason for the usage the pressure-level CARRA data results from the consistency of pressure-levels allowing an easy calculation of the vertically integrated moisture transport (IVT) following Eq. 1. Moreover, when deriving the moisture transport divergence, the values at unique pressure values do not require any further interpolation. The separation of the levels can be depicted from the dots in Fig 9-10.
In an exemplary case (not shown), we have used the model-level data and basically find higher variability in the vertical profile for wind and moisture, but the effect on IVT and IVT divergence is minor, and in particular does not change our overall results significantly (not shown). Still, we recommend using the higher resolution model data in the conclusion for follow-up studies.
Modifications: No changes made

L152f (why are radiometer/radar relevant?)
Response/Modifications: We rephrased the sentence to:
Line 211f: "We represent the aircraft location in a 1 Hz resolution, in line with the operational resolution of common airborne remote-sensing products (e.g. Mech et al., 2014; Konow et al., 2019) that can support dropsonde data."

Arctic ARs: I recommend adding a more detailed discussion about the determined characteristics of Arctic ARs (e.g., L315ff, results of Fig.1 and 10). This should involve a discussion of the communalities and differences of the presented nine cases. The large case to case variability should be better discussed.
Response: We extended the description of our selected AR events. For that, we restructured the second paragraph of the modified Section 2.2, that introduces our AR cases and split it into two subparagraphs. First, we emphasize the inter-case variability with respect to communalities/differences in the synoptic situation. Second, we describe the actual AR pathways seen for our selection (aligned to the preprint version), as follows:
Modifications (Line 165ff): "In the synoptic composition of a Greenland trough, low-pressure systems force large-scale meridional transport where ARs can evolve on the eastern cyclone flank and reach into the Arctic (Papritz et al., 2020). Similarly, blocking situations over Eurasia can favor meridional circulation. For our nine ARs (Fig. 1), we confirm a large case-to-case variability regarding the synoptic situation. While some ARs (AR2, AR3, AR4, AR9) have evolved along the eastern flank of large-scale troughs over Greenland, AR5 and AR6 are more steered by blocking high pressure over the Barents Sea. AR1 and AR7 are, in turn, reinforced by a mesoscale cyclone situated over the Fram Strait and reach very close into the cyclone center.
The synoptic compositions lead to AR dispersions over the North Atlantic and Arctic Ocean (Fig. 1), which correspond to the typical arctic moisture transport pathways identified in Papritz et al. (2021). Some ARs exhibit straight meridional moisture transport north of Iceland and approach or exceed Svalbard (AR1, AR2, AR3). AR4 and AR7 show more elongated filaments along the Norwegian coast but still reach far north. We consider eight independent AR events wherein AR5 is also considered for the consecutive day (AR6). At this stage, the centre of AR6 reaches close to the North Pole. AR8 originates from Siberia that represents another significant roadway for arctic moisture intrusions causing ARs (Komatsu et al., 2018). The last events in 2020 (AR8, AR9) are accompanied by a warm air intrusion period observed by the Multidisciplinary drifting Observatory for the Study of Arctic Climate (MOSAiC) expedition (Shupe et al., 2022), studied in Kirbus et al. (2023)."

Unclear statement", L119ff "picking (…) from catalogue")
Response: we modified the beginning of the paragraph as follows:
Modification (Line 179ff): "A caveat of our selection for making general statements about IVT variability in arctic ARs is the small sample size (nine AR cases). Therefore, we place our cases in the climatology of arctic ARs in spring. Using the entirety of spring ARs along the Atlantic pathway from the catalogue of Guan (2022), […]"
Furthermore, we put our following statements in a more logical order to clarify that our AR sample is representative for the rather strong AR cases.

2.3 Flight pattern and emulated observations

Removal of initial Section 2.1:
Response: Due to the removal, slightly more description of flight performance and dropsonde characteristics to be emulated are given in Section 2.3. In the following our remarks regarding the flight strategy will be responded.

I did not get how the flight tracks were defined. Isn't the zig-zag pattern only the consequence of sufficiently long cross-frontal legs at two latitudes that are required to capture the lateral heterogeneity and to be able to derive divergence?
Response: For the divergence purposes, the cross-frontal legs are of relevance and actually sufficient. We decided to keep our term "zig-zag pattern" due to the fact that a single aircraft has to perform an internal flight leg in order to connect both cross-sections (a relevant time constraint also for our analysis). Nonetheless, we agree to put more emphasis on the cross-section legs themselves when introducing our flight pattern. Accordingly, we will reformulate:
Modifications (Line 196ff): "Instead, the high lateral variability in AR moisture transport characteristics requires long flight legs across the AR front to better capture divergence heterogeneity. Two parallel cross-sections can be connected via an internal flight leg in a zig-zag flight pattern (Fig. 3). The zig-zag pattern observes AR corridors across its transport direction. The boundary cross-section legs perpendicular to the major flow quantify the corridor in- and outflow, i.e. in- and outgoing IVT over the entire lateral AR extension and enable simplified divergence calculations." Information about diagonal legs and the moisture budget closure will still be given, but as a site note.

Are all terminologies for the flight pattern (AR corridor, boundaries, boxes, sectors etc.) needed or would it be enough to describe two cross-sections at separate latitudes that are then classified in sectors? What defined the latitudinal spacing?
Response: We reduced the terminologies accordingly and speak of cross-section legs rather than "zig-zag" whenever sufficient. The latitudinal spacing was adapted in a way that no landmasses reduce the cross-section length in the outgoing cross-section and that the northern leg is at least 100 km away from the ingoing cross-section.
Modifications: no changes made

It is sometimes confusing what data is used. I actually thought that the flight duration was not considered for the "continuous" (L394, 426). "Continuous" was also used earlier (see e.g., Fig. 14 caption), however, I think it referred to the high-resolution cross section profiles. I suggest a clear structure and description.
Response: Precise terms are very essential for the comprehension of our work. Therefore, in our restructuring of Section 2 and 3, we added the definition of the "continuous representation" at the end of Sect. 2.3.1 to make clear that this represents the best-possible sampling of moisture transport from the moving aircraft.
Modifications (Line 216f): "This representation of meteorological values and AR characteristics will from now on be referred to as "continuous AR representation"."

L233ff should be moved to the method section.'
Response: We moved the definition of the TIVT to the Section 2.4 dealing with the sonde-based divergence derivation that this section is now more compact.
Modifications (230ff): TIVT-Definition added.

The advantages and limitations of the applied methods should be considered in view of other approaches.
Response: We extended our description of the applied methods and contrast more the advantages and limitations of our cross-section pattern for divergence calculations. One obvious limitation are the open boundaries that the cross-sections leave.

Modifications (Line 233ff): "Neglecting the moisture flux that exists apart from perpendicular to the flight track, we can approximate ∇IVT in an AR corridor by the difference of out- minus ingoing TIVT of the cross-sections. However, this excludes any divergence of the flow perpendicular to the cross-section.
The Gaussian Theorem sets the moisture flux over the perimeter of a closed surface equal to its divergence. However, our flight pattern (Fig. 3) has open boundaries at the outer sides. Only if lateral flow can be neglected, we can obtain the divergence by subtracting the inflow in the entrance leg from the streamward outflow. Given this limitation, Lenschow et al. (2007) alternatively suggests the regression method. […] Adding up both gradients, we calculate the divergence. Bony and Stevens (2019) and George et al. (2021) proved the feasibility of this method by comparing its divergence values with the Gaussian-based line integral over flown circles."

The major advantage we see in the ability of the cross-sections to derive the divergence in different sectors across the AR embedded front more or less simultaneously. Similar as in Norris et al. 2020, that investigated the airborne divergence pattern and subdivide the examined AR corridors, the sensitivity to different spatial scales can be assessed. (see answers in Sect. 2.5)

Unclear L182:
Response: We assume that the connection to the precedent sentence was unclear, as well as the vague statement of "two impacts". We rephrasedy the sentence to:
Modifications (Line 248f): "The divergence of moisture transport can be split up into two components"

I do not understand the sector classification: Please specify the "requirements" in Cobb et al. (L198ff). In L194 the prefrontal, core and postfrontal are differentiated. Then you come up with a threshold definition for the AR edges. How does this all fit together and how are the sectors defined? Please move relevant information about Arctic ARs to the introduction.
Response: We rephrased the description of our sector classification and explained the requirements of Cobb et al. in more detail, especially how we adapt those requirements to arctic conditions we found in Fig. 2.
With the term "AR edges", we mean the outer boundaries of the frontal sectors. At some lateral distance, the moisture transport (IVT) becomes too weak to be considered as atmospheric river. To facilitate the connection of our terminologies, we provide a Figure (listed as Fig. 4) illustrating the IVT-based frontal sector classification along AR cross-sections. Afterwards, we display how the sondes are located correspondingly in both cross-sections (then Fig. 5).
The requirements are described as follows:
Modifications (Line 267ff): "Therefore, we conduct a similar sector-based decomposition of IVT divergence for our arctic AR events in CARRA. As in Guan et al. (2020) and Cobb et al. (2021a), our decomposition relies on the IVT characteristics along the cross-section, which we depict for an exemplary cross-section in Fig. 4. The central AR core represents the region of strongest IVT, which is more than 80% of maximum IVT (IVT_{max}). East of the core we situate the pre-frontal sector and west the post-frontal sector. Yet, their outer edges are less trivial as ARs basically have open outer boundaries. To account for case-specific relative values, we assign frontal edges where $IVT \leq 0.33\, IVT_{max}$. As a secondary absolute threshold, we declare a moisture transport with $IVT \leq 100$ kg $m^{-1}s^{-1}$ as too weak to be assigned as AR-IVT. Both form the outer edges of the AR where the pre- and post-frontal sectors end (Fig. 4). Note that the latter threshold to define the AR edges follows the approach of Cobb et al. (2021a). However, we lower their mid-latitude based IVT threshold from 250 to 100 kg $m^{-1}s^{-1}$. By this, we refer to common polar moisture transport magnitudes that exceed the 95th percentile of climatology and are declared as ARs in the detection of Guan and Waliser (2015). Otherwise, we would either exclude most ARs north of 70◦N, or would shrink the AR cross-section so much that most transport is ignored, as statistics in Fig. 2 suggest.

Applying the frontal classification to both cross-sections, we obtain three sectors. For the cross-sections of the AR, we locate the sondes so that six synthetic sondes (three each from the in- and outflow cross-section) span each frontal sector and calculate its IVT divergence, respectively (Fig. 5). Inspecting the sonde positions in Fig. 5, we emphasise that our IVT -determined frontal AR sectors along the flight track tilt while the internal IVT has a straight northward orientation. This arises from the north-eastward displacement of the AR filament over the course of the 2.5 h synthetic flight section (Sect. 2.3). Accordingly, Sect. 5 examines the extent to which sonde-based IVT divergence is affected by flight duration, as opposed to actually looking at the AR in an instantaneous snapshot.”

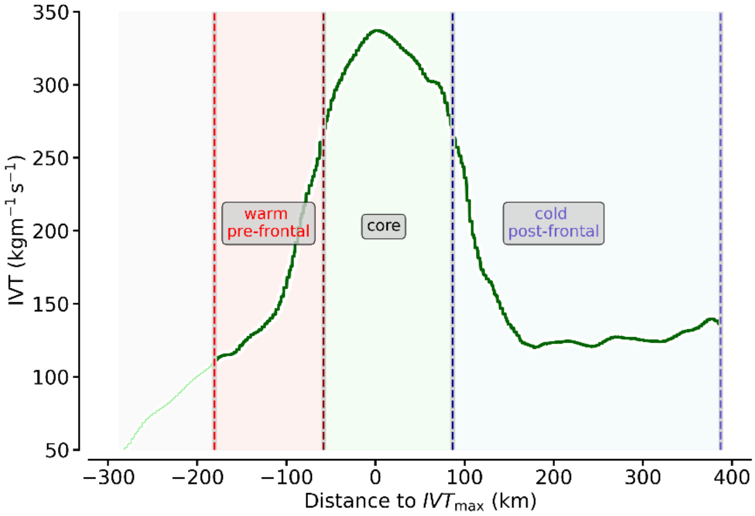

Figure 4 (in manuscript): Frontal sector decomposition for an exemplary IVT cross-section (AR1) using the criteria described in Sect. 2.5. The colored shadings and text boxes indicate each frontal sector. The grey shading on the left represents moisture transport (i.e. IVT) that is not considered as AR because it is too weak.

Section 2 specific comments:

L202: I cannot see the three dropsondes that calculate IVT.

Response: We specified our misleading explanation:

Modifications (Line 279ff): “Applying the frontal classification to both cross-sections, we obtain three sectors. For the cross-sections of the AR, we locate the sondes in a way that six synthetic sondes (three from the in- and outflow cross-section each) calculate the IVT divergence for each frontal sector respectively (Fig. 5).”

L204 (putative? inconsistency?)

Response: we deleted both words as they do not provide any added values.

Section 3: Moisture transport in Arctic AR cross-sections from soundings

General remarks:

The paper lacks a thorough discussion of the results, either within the result section or in a separated section at the end. [..] a few references within the result section, however, not detailed enough (see above) so that the added value of the paper becomes clear.

Response: We agree that the discussion of results is worth improving. We decided to manifold and strengthen the discussions in the respective result sections rather than merging them in a separated “discussion” section. Therefore, we restructured concerning paragraphs in order to unravel the discussions of results more stringently. We strengthen the interpretation of our results in a more connected comparison to findings from literature (mostly based on mid-latitude ARs). In the following, you find specific responses for the relevant sections, whereby many reviewer remarks are applicable for several paragraphs throughout our results sections.

Add more references to figure panels within the text whenever appropriate.
Response: Yes, this improves readability. We added them especially in our result sections.

Sect. 3.1: Shape of IVT across arctic ARs

I recommend adding more detailed discussion about determined characteristics of Arctic ARs.
Response: We take up this point for Sec 3.1, as the IVT shape of ARs in the Arctic is here first presented in more detail. We find that comparisons are helpful here to categorize our cases. Accordingly, we added some more discussions about the IVT strength for our AR cases with respect to mid-latitude cases (Cobb et al, 2021) and arctic cases studies (Viceto et al, 2022). This is done as:
Modifications (Line 299ff): "Summarising all cross-sections of our ARs from Sect. 2.2, most arctic AR cross-sections show this typical bell-shaped IVT curve over widths of roughly 400 -800 km and indicate pronounced IVT maxima in the core of 300-600 kg m^{-1} s^{-1} (not shown). Only for the weak AR8, this structure is less pronounced. We find that the arctic AR are not substantially narrower than the AR widths of global climatology (Guan et al., 2015) or observed mid-latitudes events (Cobb et al., 2021). Flight planning should thus consider cross-section distances of around 500-1000 km, similar to mid-latitude ARs. However, this only applies if the legs are not restricted to regions with IVT>250 kg m^{-1} s^{-1}, which is a widely used threshold for mid-latitude ARs (e.g. in Ralph et al., 2019). In contrast, the maximum IVT for the arctic events, is roughly half as high as the majority of mid-latitude AR from airborne studies in Cobb et al., 2021. Moreover, the IVT magnitudes strongly differ between our cases and synoptic conditions. The strongest ARs with maximum IVT (IVT$_{max}$) exceeding 500 kg m^{-1} s^{-1} are found for intense Greenland troughs, while the ARs are weaker along the Siberian pathway (see Fig. 1). If we compare our ARs with those of other arctic case studies (e.g. Viceto et al., 2022), we are looking at rather strong ARs."
Additional Response: We specified the comparison between ERA5 and CARRA: Modifications (Line 310ff): **"Viceto et al. (2022) documented the improved representation of arctic AR characteristics in ERA5 against coarser reanalysis data. In our comparison of CARRA and ERA5, the location and horizontal pattern of the ARs agree quite well (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 horizontal resolution being higher than in ERA5."**

Should there be a strategy to place one dropsonde at a simulated maximum IVT (L223)?
Response: The restructured discussion of results follows this suggestion as:
Modifications (Line 315ff): "Using a set of six synthetic sondes, a gaussian fit of IVT can reproduce the bell-shaped AR-IVT cross-section (Fig.6). This gaussian fit is very sensitive to the actual positions of dropsonde releases. While the centered sonde in Fig. 6 is positioned close to IVT$_{max}$, a slight shift of this sounding, which easily occurs in real observations, can quickly lead to an underestimation of the moisture transport in the AR core. Flight planning should thus imply a sonde release in the vicinity of predicted IVT$_{max}$ and place additional sondes symmetrically around the core. While sonde positions in Fig. 6 are suitable to represent the cross-section IVT, other AR cross-sections evince more complexity in being accurately represented by this number of soundings. We need further inspections on how sounding intervals deteriorate the AR moisture transport observability."

Sec. 3.2 Sonde-based total cross-section moisture transport

I suggest adding a recommendation for the spatial separation (L252, L425) instead of a number per flight which depends on the flight performance. Figure 6: Change "seconds" to "minutes".

Response: Indeed, a recommendation for the spatial separation is more universal with respect to flight performance. We changed the descriptions in this way and we also changed the axis of Fig. 6 to distances (km). Yet, since measurement operators frequently rely on specified time intervals when performing sonde releases manually, we add a light secondary axis referring to the spacing time. It is true that the duration depends on the flight performance, however, the values are valid for a common groundspeed at cruising level above 10 km.

Modifications: Updated version of Figure 6 (now Fig. 7):

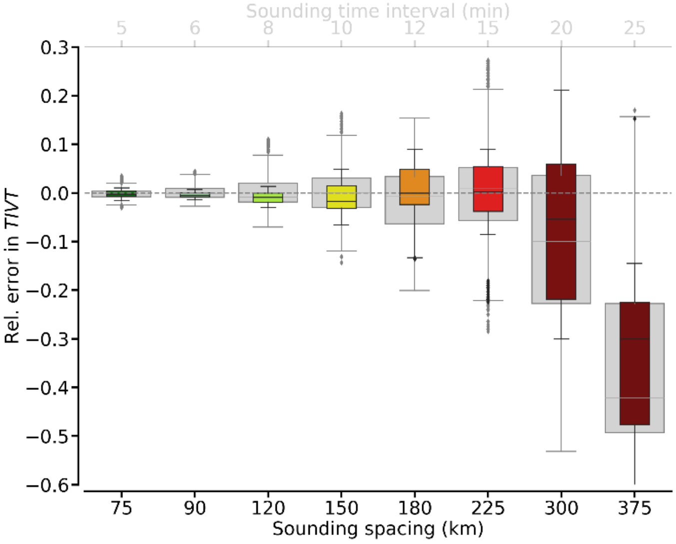

Fig. 6: The median lines for the grey boxplots are hard to see. I guess that these distributions are calculated from the boot-strapping method (add information to caption). How many cross-sections? Please add what percentiles the box and whiskers represent.

Response: We added the information about the median lines, that are now illustrated bolder. We change seconds to minutes. The qualitive meaning of the colour-coding is specified in the caption. The statistics are based on the boot-strapping approach considering hundred positions of sondes per cross-section. In total, this includes 900 cross-sections. The boxes show the quartiles while the whiskers extend to show the rest of the distribution, except for outliers (depicted as markers).

Modifications (Figure 7 caption): "Relative error in TIVT as a function of sounding spacing in km for all AR cross-section representations (grey) and those including highest (75th percentile) IVT maxima (coloured). Statistics rely on the boots-trapping approach containing of 100 cross-section sonde representations per AR. The boxes show the quartiles while whiskers show the rest of the distribution, except for outliers (markers). For an assumed aircraft speed of 250 m/s, equivalent release intervals are given on the top x-axis."

How sensitive are these results to the length of the flight pattern?

Response: Indeed, the TIVT values are always dependent on the flight lengths. We also compared the TIVT values of the arctic ARs in more detail with mid-latitude observations, where we also point out the different AR widths between arctic and mid-latitude ARs, if one would restrict to the same thresholds defining the outer edges. Regardless the actual AR width on which we also align the flight length, we stick to our recommendation of seven sondes that should be envisioned to be released in order to derive IVT divergence in the three different frontal sectors (pre- and post-frontal, and the core). Since the stronger ARs (in terms of IVT_{max}) are also broader, Fig. 7 demonstrates that the minimum required sonde spacing is less sensitive to the actual AR width. However, we admit that robust conclusions in this sense should involve a much higher number of AR events. The discussion of the arctic TIVT values is done as follows:

Modifications (Line 339ff): "The TIVT uncertainty in Fig. 7 increases less rapidly with larger sonde spacing than derived for mid-latitude AR cases (see Ralph et al., 2017 and Guan et al., 2018). Total moisture transport in the arctic cases is, in turn, much smaller than in mid-latitude cases. The arctic TIVT values are roughly half as high as the sonde-based mean TIVT of 5 10^8 kg s^{-1} ascertained by Ralph et al. (2017) from 21 mid-latitude ARs. The ARs we consider have, in turn, roughly two third the width of the ARs in Ralph et al. (2017) and Guan et al. (2018). Here, we remind that our threshold to define the outer AR edges is much lower to encounter for arctic AR conditions. Applying the mid-latitude thresholds (given in Sect. 2.5), mean AR widths would be in range of a few hundred kilometer and T IV T values much lower than in mid-latitude ARs."

Sec 3.3: Variability of moisture and wind in arctic ARs

Response (according to a more detailed discussion) and vague relation to other studies (L266f): In this section, we also put more emphasis on clearly disentangling results (e.g. Fig. 7) and discussions that we manifold. We compare vertical profiles in Fig. 7 with those of radiosondes in an arctic early summer AR period studied in Viceto et al. (2022) and synthesize communalities and differences to mid-latitude AR soundings in more detail:
Modifications (Line 368ff): The vertical moisture characteristics in Fig. 8b) resemble soundings of arctic early summer ARs at Ny-Alesund demonstrated in Viceto et al. (2022) who showed q values up to 5 g kg^{-1}. However, the winds in our AR cross-sections (Fig. 8a) are roughly twice as strong as given in the case study of Viceto et al. (2022). Note that the ground-based station from which Viceto et al. (2022) depicted soundings were basically located at the outflow edge of the AR (with IVT ≤ 250 $kgm^{-1}s^{-1}$) on the Luv side. Winds from the east were orographically slowed down by the massif of Svalbard. In this sense, the marine arctic ARs we consider are undisturbed. This enables stronger winds whose magnitude is rather comparable to mid-latitude AR conditions. Ralph et al. (2004) and Cobb et al. (2021b) report on mean low-level wind speeds from 10–25 m s^{-1} for a large set of ARs over North-East Pacific. The slight local wind maximum at 900 hPa (Fig. 8a) arises from the presence of strong wind corridors designated as LLJs that represent a common feature in mid-latitude ARs (Ralph et al., 2004; Demirdjian et al., 2020). Their polar existence is verified in the case study of Terpstra et al. (2021). We find a very dominant LLJ inside our most intense AR (AR3 in Fig. 8). Above the local wind maximum, the vertical profile of wind speed remains more homogeneous than in sub-tropic/mid-latitude cases where Ralph et al. (2005) and Cobb et al. (2021a) registered a stronger intensification with height.

L274f: How can you see this in Fig.8 (7 before)? Winds also strongly vary and the transport distribution (grey shading) resembles the wind distribution (red shading). The sentence in L275f contains redundant information.
Response: We referred imprecisely to the strong AR case (AR3) represented by error bars and not by the shadings in Fig. 8. Now, we compare our descriptions for the entirety of ARs and AR3 more obviously and rephrased the discussion of moisture transport variability and the role of wind and moisture:
Modifications (Line 380ff): "The cross-section variability of both moisture and winds strongly affects IVT variability. The shadings in Fig. 8 indicate that the standard deviation of moisture transport resembles the standard deviation of the winds for the lower levels up to 850 hPa, before moisture transport variability is apparently driven by the standard deviation of moisture in upper levels, although the wind standard deviation becomes highest above 500 hPa. For the most intense AR3, the LLJ exhibits high wind speeds above 30 m s^{-1} that cause strong moisture transport whereas moisture is more or less average. While strong moisture transport in AR3 originates from overall strong winds, moisture varies strongly and seemingly dominates the moisture transport variability. Hence, we hypothesise that in strong arctic ARs with intense winds, moisture

variability primarily steers IVT variability and leads to the bell-shaped IVT cross-section pattern (Sect. 3.1).”

L285f: Do you have an explanation for the increased variability in the free troposphere? Fig. 10 shows that your cross-sections pick up dry post-frontal subsidence regions and also dry Arctic air eastward of the AR feature, which likely impacts this result. Or maybe this is what your last sentence wants to say? How much sense does it make to calculate horizontal means for such heterogeneous sections?

Response: Indeed, the subsidence of dry airmasses is one of the major explanations for the increased variability in q. As referred to Fig. 10 by the reviewer, we take up with this question again in Sec 4.4. Here, Fig. 11 enables an illustrative explanation.

The reviewer’s last remark opens a very crucial discussion that results from the question of what do we consider as the “AR itself”? Here, the scientific perception strongly differs between the horizontal and vertical perspective. In the large majority (and as this study does), moisture transport with respect to vertical integrated quantities (IVT and/or IWV) is designated as AR where a certain threshold is exceeded. Even if the thresholds may change between AR detection algorithm for various reasons, they mostly have in common that they project the AR from 3D (horizontal and vertical) to 2D (horizontal). No matter if different air masses are entrained at certain vertical levels, the domain is still considered as AR, as long as moisture / or moisture transport are sufficiently high in the vertical integral.

The vertical atmosphere may thus still hold two airmasses (dry post-frontal subsidence regions and a moist air mass smaller than the ‘plume’ in the AR core). How both airmasses interact across this interface is a question for itself. The degree of mixing can have strong impact on cloud and precipitation formation (beyond the scope of this study). However, due to this fact, we pretend that is worth to consider such edges where we find a coexistence of air masses. Also, in the perspective of practical flight planning, forecasts of IWV and IVT represent the quick identification of the AR object to locate the flight tracks in.

Modifications: no changes made

Wouldn’t it be more interesting to focus on the AR itself and check how much the fluctuations at small scales contribute to IVT?

We highlight that we applied our cross-sections with respect to the AR edges from the AR catalogue (Guan, 2022) and can confirm that less than 5% of the flight tracks reach out of moisture transport that is declared as AR. This can also be seen in Fig. 11, where the AR edges (outer edges of the frontal sectors) are partially even more restrictively defined than in Guan (2022). Accordingly, we assure our results are representative for AR internal variability. By our frontal decomposition, we also put more focus of the central AR core.

Modifications: no changes made

Sect. 3.4: Coherence of moisture and wind

L289-291: Better explain the meaning of “correlated” and “coherent”.

Response: we specified that we mean the correlation of both variables along the cross-section and here now speak of “connected pattern”. We stated more explicitly that the non-coherent transport consists of the individual means of moisture and winds ($\overline{q} \cdot \overline{v}$).

Modifications (Line 400ff):”For the moisture transport, it is not only important whether moisture and wind anomalies are high separately (Sect. 3.3), but also how correlated they evolve along the AR cross-sections and whether connected pattern contribute significantly to AR-IVT (Q2). If both pattern do, carefully collocated observations are essential to determine TIVT , otherwise independent estimates of mean moisture and wind are sufficient. The overall moisture transport […] is basically a combination of transport by the mean quantities q and v and their correlated cross-section variability, i.e spatial fluctuations q′ and v′[…]”

Like for Fig 10: This should involve a discussion of the communalities and differences of the presented nine cases. The large case to case variability should be better discussed.
Response: We restructured the paragraph describing now Fig. 11 and insist in more detail on large case-to-case variability with more direct relations to the references given. We extended the discussion to mid-latitude ARs and focused on the discrepancies to AR schematics as in Ralph et al., 2017 when arctic wind and moisture pattern do not coincide. We highlighted on the differences in AR corridors that are closer located to the AR center (e.g. AR5) against those corridors situated in the outflow region (e.g. AR7/9). We referred to Terpstra et al. 2021 that detected missing coincidence in a polar AR outflow, but rather in the vertical axis than we do in the horizontal.
With the added comparison, we specify the role of dry subsiding airmasses that become more effective if there is upper-level advection from Greenland air masses. We note that our analysis from Fig. 11 can still be manifold in various perspectives and details. At a certain point, however, we need to refocus on our research question and investigate the correlation between moisture and wind for the given cases and how the patterns contribute to IVT and its variability.
Modifications: Rewritten part (Lines 432-453) according to descriptions above

Section 3 specific comments:

L225 (maintain?)
Response/Modifications: Changed to "show"

L322f: If there is little information from small scale fluctuations, why should one care about supplementary q observations?
Response: Yes, this is valid point. However, if one is still willing to improve the measurements, then one should focus on supplementary moisture observations.
Modification (Line 458): "An improvement for observing the moisture transport variability should be built upon supplementary moisture measurements rather than those of the winds."

L260 (why intuitive?),
Response/Modification: rephrased to "simplified"

L268 (behaves more homogeneous?),
Response/Modification (Line 378): changed to: "**remains more homogeneous"**

L277 (How?)
Response/Modification (Line 388f): rephrased to: **"The identification of the more variable quantity can improve measurement strategies. Specifically, moisture can be derived from supplementary remote sensing devices on long-range research aircraft."**

L278 ("long-term aircraft"?)
Response/Modification: typo, changed to long-range

L289-291 (e.g., "carefully correlated observations?", "cross-sectoral")
Response/Modification (see above Line 400ff): changed **to "collocated" and "cross-section variability"**

L322 ("narrowed moisture columns here form"?)
Response/Modification (Line 455f): Rephrased to: **"Instead, narrow and high-reaching moisture plumes in the core control the moisture transport variability."**

Section 4: Moisture transport divergence from sondes

4.1 Sectoral in- and outgoing moisture transport

Fig. 11 "frontal specific AR sectors" is unclear. I […] wonder that the dotted lines at negative distances are warm pre-frontal areas? I do not understand the two sentences "Leg specific … (lines)" – please rephrase. What is "corridor IVT convergence"?

Response: We rephrased the figure caption.

Modifications (Figure 12 caption): "Figure 12. IVT along inflow (outflow) section in blue (orange) for all nine ARs (Fig. 1). Changes in line styles denote the frontal sector classifications (Sect. 2.5): Dotted lines represent cross-section periods attributed to pre-frontal sectors, while dashed lines refer to post-frontal sectors. The legend depicts TIVT values for the in- and outflow cross-section parts within the AR. They include IVT purely internal of determined AR borders (Sect. 2.5). Arrows indicate the TIVT difference between in- and outflow leg scaled in length and width. The differences can be viewed as simple estimates of IVT divergence in between both legs, according to Sect. 2.4. Upward (downward) arrow scales represent estimated convergence (divergence) magnitudes. Note the x-axis orientation is from east (left) to west (right). "

It did not become clear to me how the cross-sectional IVT gradients (Fig. 11) are connected to the dynamical situation and the results are contrasting the impression that I got from Fig. 1.

Response: We suppose that the axis orientation confuses the reader. Negative distance values refer to the eastern end, while positive values refer to the western end of our cross-section legs. Thus, the cross-section pattern should be mirrored when comparing with Figure 1. We added the clarifying explanation in the Figure caption (see above).

Then we cannot detect such inconsistencies to Figure 1. For example, the steep decline in the post-frontal sector of AR2 (Fig. 11b) is well in conjunction with IVT pattern shown in Fig. 1. Similarly, the gradients of in- and outflow legs for AR2 & AR7 are consistent with the outflow IVT pattern in Fig. 1. Later in the section, we highlighted that a comparison for estimating IVT divergence can be misleading in some cases. Note that IVT cross-sections are (although continuous) based on flight duration and not on an instantaneous snapshot as from Fig 1.

Modification (Line 489ff): Nonetheless, although the IVT pattern of AR5 and AR6 (Fig. 1) allow slight divergence in the pre-frontal sector, we emphasize that a TIVT-based interpretation of predominant moisture transport divergence underlies strong idealisation. It considers neither moisture flow being non-perpendicular to the flight, nor it does separate contributions of moisture advection and mass convergence. Therefore, we insist on the regression approach to diagnose moisture transport divergence in each frontal sector of the arctic ARs.

The TIVT discussion (Fig. 11) could focus more on the AR area: Why is the divergence dominating in what you call warm sector – isn't that surprising?

Response: We restructured the section: The first paragraph covers TIVT as a whole, the second paragraph the cross-section differences, the last paragraph investigates in more detail the TIVT gradients for the frontal sectors. We will highlight surprising findings more, but point out the limits in estimating divergence purely from IVT magnitudes.

Modifications (L477ff): "Figure 12 further separates the AR cross-sections in the three sectors (pre-frontal, core, post-frontal). Although the AR cores are roughly 200–300 km narrow (slim lines in Fig. 12), they provide more than half of the entire AR-TIVT. This contribution of the AR core agrees with findings from Cobb et al. (2021a) in mid-latitude ARs. Except for AR2 and AR7, weaker slopes of IVT are generally in the cold sector as opposed to the warm sector. In turn, the steep post-frontal decline of *IVT* in AR2 and AR7 results from calm air masses on the backside of the AR (see also Fig 11).

Comparing both legs (Fig. 12), cross-section TIVT tends to decrease downstream in some arctic ARs. Yet, we likewise identify cases with weak stream-ward tendencies in total moisture transport or with slight increases. Moreover, the downstream difference

of TIVT is distributed unevenly over the cross-section IVT. It is mainly within the AR core where IVT decreases towards the outflow leg (e.g. AR3, AR9), thus suggesting internal convergence. However, counteracting behavior in the frontal sectors partially compensates the core and stream-ward decrease of IVT. Like in AR6, the increase of warm sector IVT towards the outflow conveys a seeming divergence in the warm sector. This is in contrast to the findings in Guan et al. (2020), where the pre-frontal sector is denoted as a region of moisture transport convergence. Nonetheless, although the spatial IVT pattern of AR5 and AR6 (Fig. 1) allow slight divergence in the pre-frontal sector, […]"

It is sometimes confusing what data is used. I actually thought that the flight duration was not considered for the "continuous" (L394, 426). "Continuous" was also used earlier (see e.g., Fig. 14 caption), however, I think it referred to the high-resolution cross section profiles. I suggest a clear structure and description.

Response: We apologize for the missing clarity of the term "continuous". We added a clear statement in the method section (2.3.1) that underlines our definition of "continuous" cross-sections. The manuscript refers to the Sect. when speaking of "continuous" in the remainder of the study.

Section 4.2: Sonde-based divergence and its representativeness

missing detail about the related work: L352f, L355f, L358f:

Response: We specified our reference to related work and stated more precisely how we build on the precedent studies of Guan et al. (2020) and Norris et al. (2020).

Modifications (Line 495ff): "This section specifies the IVT divergence (∇IVT) in arctic ARs. Using the regression-based ∇IVT (Sect. 2.4), moisture transport divergence is examined for the frontal sectors (Sect. 2.5) and for the decomposed terms, namely moisture advection *ADV* and mass convergence *CONV* (Eq. 5). Again, the results from the continuous cross-section flight legs (Sect. 2.3.1) represent our idealized reference. We compare them to regression-based results referring to seven synthetic sondes per cross-section (as in Fig. 5). This comparison assesses uncertainties of sonde-based ∇IVT, representative for arctic ARs. In doing so, we build on Norris et al. (2020) who pioneered the airborne derivation of all moisture budget components, including moisture transport divergence, by sampling a mid-latitude AR event."

Modifications (Line 518ff): "The fact that the moisture transport divergence components differ across the frontal axis is in line with mid-latitude AR based statistics of Guan et al. (2020). In detail, the characteristics in AR3 described above differ quietly to the AR case observed by Norris et al. (2020). In their airborne study of an mid-latitude AR, they found moisture transport convergence to be strongest close the AR core and rather opposite signs for the pre- and post-frontal regions than us. Especially the lack of pre-frontal moisture advection in AR3, which Guan et al. (2020) actually robustly found in mid-latitude AR statistics, is worth-mentioning. In contrast to both Norris et al. (2020) and Guan et al. (2020), we do not identify a dominance of dynamical convergence over advection. The magnitudes of moisture transport divergence in AR3 are also much lower. Nonetheless, we remind that Norris et al. (2020) and Guan et al. (2020) consider even more intense mid-latitude AR near its centre. While AR3 is exceptionally strong for arctic conditions (Fig. 2), it is rather moderate for mid-latitude scales (Ralph et al., 2019)."

Section 4 specific minor comments:

L333ff (What is the "simplified understanding of divergence"?, "benchmarks…"?)

Response: We merged both expressions in a connected sentence.

Modifications (Line 470ff): "The comparison of *TIVT* in both legs reveals first simplified estimates of the prevailing divergence. Idealising that no entrainment into the AR corridor (Sect. 3) takes place, Figure 12 contrasts TIVT of the in- and outflow cross-section to estimate whether convergence or divergence of moisture transport exists inside the AR corridor."

L358 ("behave differently"):

Response/Modification (Line 502f): formulation rephrased: **"*ADV* and *CONV* exhibit different vertical profiles throughout the frontal cross-section"**

L360 ("lower atmosphere")

Response: deleted

L364f ("integrate along the vertical axis")

Response: The respective sentence was removed as it is invalid for the updated results

L373ff unclear

Response/Modifications (Line 531ff): We reformulated the sentences to: "When we place our sonde results in the context of the airborne study by Norris et al. (2020) using real dropsondes, we recognize the strength of true sondes with a high vertical resolution. They provide much greater vertical variability. Thus, it is likely that the quite low divergence displayed in Fig. 11 does not only result from less divergence prevailing in Arctic ARs compared to mid-latitude ARs, but may also be a consequence from the coarser vertical grid that average out larger values."

L392 ("our arctic AR composition"?)

Response: changed to: "for our sample of arctic ARs"

Section 5: Deterioration by non-instantaneous sounding

Section 5: Specific minor comments

L403f (unclear)

Response: reformulated:

Modifications (Line 582ff): "This section examines the extent to which the temporal AR evolution during flight affects the sonde-based representation of IVT divergence. Up to 3 hours are needed to fly over AR corridors and consecutively observe the in- and outflow (Sect. 2.3.1). Meanwhile, temporal AR evolution can distort the airborne (non-instantaneous) representation of IVT divergence in the AR."

Section 6: Summary and Conclusions

[…] *should synopsize and synthesize the key results and identify the contribution to research on Arctic ARs. I think it will strongly profit from an improved discussion of the results.*

Response: In the following, we improved our conclusions in terms of clarity in structure and the discussions of our key results.

So far, the first paragraph is a repetition of what was done. The second paragraph claims that higher resolution reanalyzes increase our understanding of arctic moisture transformation and precipitation efficiency, which I don't see is addressed.

Response: We split up the first paragraph. In accordance with the remarks of reviewer 2, who suggests to put more emphasis on the general arctic AR conditions rather than airborne

perspective, we restructured our conclusions. First, we approach the concrete perspective of our study (the observability of arctic AR IVT divergence by dropsondes). In our opinion, it is helpful to briefly repeat how the synthetic soundings were established to answer our research questions. In the second paragraph, we synopsize the basic AR-IVT characteristics in the Arctic we found before specifying the airborne perspective. By that, we got rid of the initial second paragraph which lacked clear structure and key messages. Instead, we summarised our considered IVT magnitudes in the Arctic and how they differ to mid-latitude ARs
Modifications (Line 637ff):
"This assessment study investigated the characteristics of the moisture transport divergence in arctic Atmospheric Rivers (ARs). We analysed the ARs from an airborne perspective to assess the dropsonde-based observability of moisture transport divergence of arctic AR. We characterised airborne uncertainties in sonde-based representation of the AR moisture transport divergence inside arctic ARs, focusing on two sonde-based limitations: subsampling by too large sounding spacing and the non-instationarity of the AR over the flight duration. For this, we followed a synthetic approach using reanalysis data a virtual truth. CARRA reanalysis data were interpolated on synthetic flight pattern that consist of two cross-sections covering frontal sectors over the entire AR transect. Single vertical profiles emulate dropsondes.
We considered nine arctic AR events over the Atlantic pathway to the Arctic ocean in the vicinity of the sea-ice edge from last decade. The values of Integrated Water Vapour Transport (IVT) in the AR cores range from 300-600 kg m^{-1} s^{-1}, although the ARs are primarily examined north of their center. We thus classify these AR as rather strong for arctic conditions. Still, the bell shape of IVT across the AR varies strongly in between the AR cases. The considered cases cover a large variability and consist of various synoptic pattern (extended troughs, blocking situations, single cyclones) in which the AR are embedded. This study delivers benchmarks of uncertainties in the airborne representation of sonde-based AR moisture transport divergence. We conclude the four pursued questions (Q1-Q4) as:"

The reason for summarising our synthetic framework is to remind the perspective that our feasibility study has chosen. We are confident that such a repetition of the synthetic approach facilitates the readability in later discussions, as well as the interpretation of our conclusions. Nevertheless, we erased too detailed information (e.g. the regression method used).

The authors should try to better synthesize the central message of their results to each of the RQs in view of the gained knowledge. I suggest a separate discussion of how the obtained results may affect future flight planning and the deployment of dropsondes (Q1, Q4).
Response a): We updated the central messages to our research questions and conducted a stronger connection to individual flight planning which is achieved by an improved structure. We extended the specifications in our recommendations for future dedicated flight planning.
Modifications (Line 652ff): "For the sonde-based determination of Total Integrated Water Vapour Transport (TIVT) in arctic AR cross-sections, sonde spacings below 100 km robustly keeps TIVT errors below 10 % (Fig. 6). In strong ARs with IVT exceeding 500 kg $m^{-1}s^{-1}$, too coarse IVT representation at the AR core leads to TIVT underestimation. Gaussian fits help to reproduce the cross-section IVT shape but are sensitive to how sondes estimate maximum IVT and its location. Thus, precedent flight planning should aim for a sonde release at forecasted IVT maximum and place additional sondes symmetrically around. For arctic AR widths of 400-800 km, we suggest a minimum of seven soundings per cross-section (roughly 60 to 120 km spacing) to derive TIVT in both cross-section legs. The maximum IVT is more correlated to IVT variability than the AR width is. The planning of sonde releases should thus rely on the steepness of IVT along the cross-section. We highlight that the differences of TIVT between the in- and outflow cross-sections are in a range of 2-15% (Fig. 12). If we want to reliably estimate moisture transport divergence based on TIVT from both cross-sections, the sonde-based uncertainty of TIVT for a single leg must be considerably lower."

Response b): We already gave some suggestions for future flight pattern in the preprint's conclusion, but in a poor structure. Now, we improved the structure of our concluding implications on flight planning emerging out of the conclusions from Q1-Q4.

Modifications (Line 698ff):" We confirm the observability of moisture transport divergence in arctic AR corridors by releasing sondes in such dedicated flight patterns. A maximum sonde spacing of 100 km within the AR cross-section can in principle characterise the divergence between both cross-sections at the given uncertainties of ≤ 10 %. For the flight durations, we obtain the entire moisture transport divergence specified for the frontal sectors with an uncertainty in the range of 25-50 %. We deduce that sonde undersampling matters and recommend a sequence of at least seven sondes per section given the widths of arctic ARs. However, notwithstanding that we could release a higher number of sondes, it is the temporal AR evolution over flight duration that leads to higher deviations in the divergence components rather than sonde undersampling. The dedicated planning of such sonde-based purposes should not only include the positioning of the sondes, but also the minimisation of the flight duration. The placement of the cross-section legs and their spacing should carefully consider the AR displacement during flight. Shorter meridional distances between the cross-sections not only reduce the flight duration, but also the area enclosed by the sondes. Given the frontal-sector widths of the arctic ARs, both cross-sections should be no more than 200 km apart. For several of our cases, the meridional separation is higher and we have to expect considerable sub-grid scale variability. Collocated flights by two aircraft, with both cross-sections being not far apart and sampled simultaneously, is the optimal and still feasible strategy. When faced with a limited amount of dropsondes, supplementary measurements of moisture should be prioritized, as moisture represents the more variable quantity and moisture advection mostly dominates the moisture transport divergence in the AR corridors."

Response c): After these implications we added a description of the limitations of our study that covers several points mentioned in the reviewer's remarks (vertical resolution of CARRA used, limits of regression approach. We used the constrains to provide specific suggestions for arctic AR follow-up studies using CARRA.

Modifications (Line 713ff): "Additional limitations of our study need to be discussed. As our results are mainly based on corridors in the AR exit region, we strongly recommend extending our uncertainty assessment to other AR regions and expect the role of winds and mass convergence to increase in strong ARs. This becomes an even more important issue with respect to the tendency of arctic ARs to shift more northward and intensify under climate change (O'Brien et al., 2022). Furthermore, as we include a large variability of synoptic AR patterns but a small sample, we propose statistics with a larger number of AR events. The statistics can improve our understanding of the moisture transport divergence pattern in arctic ARs and attribute it to the dynamic and thermodynamic atmospheric conditions. Here, CARRA represents a very suitable reanalysis framework for this purpose in follow-up studies. Again, we encourage the use of the higher vertical resolution of the model levels rather than our chosen pressure levels, although sufficient for initial estimates. For real sondes, we emphasise the added value of their high vertical resolution. Sondes provide more accurate information on the vertical composition of ADV and CONV. The sonde-based approach is limited to regression-based divergence where we consider only rather large areas and open meridional boundaries. Even with continuous lateral sampling, the meridional gradients are only coarsely sampled.

Therefore, a follow-up study should investigate how the arctic AR moisture transport divergence acts internally of the flight corridor at grid-cell scales. This will allow two additional research topics to be addressed: First, the internal variability between both

cross-sections can be derived more precisely to improve the flight pattern, second the actual scales at which the moisture transport divergence varies significantly can be evaluated. This may also increase the divergence magnitudes, similarly to Norris et al. (2020) who found larger values of the divergence components. They considered smaller airborne AR corridors than the ERA-Interim pixels referred to in Guan et al. (2020).”

Response d): Finally, we summarize the necessity of assessing the sonde-based observability and of deriving uncertainties for model-observation inter-comparison.
Modifications (Line 731): Despite the aforementioned limitations, the orders of magnitudes for IVT variability and divergence that we provide are representative for arctic ARs and quantify benchmarks in the sonde-based derivation. Consistently mimicking the soundings is a fundamental step towards the understanding of the uncertainties when such airborne tactics are actually carried out. The benchmarks are not only useful for improving flight strategies, but also indicate deviations in corresponding model-observation comparisons. Only by illuminating the constraints on the AR representation from both models and observations, we establish a framework from which airborne observations can support modellers in terms of the resolution and complexity required for the parameterisation of moisture transformation processes caused by IV T divergence in arctic ARs.

L485 (unclear)
Response: changed.
Modifications (Line 673f): “By contrasting in- and outflow TIVT through the AR transects, we expect an overall divergence in moisture transport.”

II) Response and Changes to the Comments from Anonymous Referee 2 (AC2)

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*). The changes/modifications in the manuscript are specified below (**bold**). 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 (from now on denoted as AC1), because several answers in AC1 consider the remarks given from Referee 2 and we intend to avoid repetition.

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 had to be carved out more clearly. We are confident that the specification significantly improves the readability and clarity of the manuscript. Accordingly, we focused 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 carefully rewrote the introduction which, based on the reviewer remarks, we identified as one of the major weaknesses of our manuscript.

In detail, we specified our changes in structuring the motivation of AC1. At this point, we summarize some of the changes that we declare as most relevant according to Reviewer #2: The first paragraph now states more explicitly the presence and impact of Atmospheric Rivers (ARs) in the Arctic. We now refer to a broader collection of studies with respect to the Arctic and concretise 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. Finally, it disentangles the issue and research gap, which is the lack of quantitative estimates for IVT divergence within Arctic ARs.

Modifications: see AC1 in I) above

"*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 a): The second paragraph is a logical transition to the description of the required measurement strategies to derive IVT and highlighting the need of in-situ sampling to obtain the moisture transport throughout the troposphere. In the third paragraph, we now address this point in more detail: We added 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. 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.

Modifications (Line 49ff): "Radiosondes allow detailed insights of moisture transport profiles of arctic ARs at individual locations (e.g. Viceto et al., 2022), but their observation network in the Arctic is too sparse to obtain the divergence in single ARs (Dufour et al., 2016). Similarly, dropsondes released from research aircraft can also provide vertical profiles of relative humidity and wind speed with an accuracy of 1 % and 0.1 m/s, respectively (e.g. George et al., 2021; Konow et al., 2021)."

Response b): Both referee reviews demonstrate the need of 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 (4th paragraph). 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 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)

Modifications: no change made in the manuscript as too detailed and distracting

Response c): The changed order in which we introduce our research questions sequentially, rather than at the end of the introduction as in the preprint, intends 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 dealing with the structure of arctic ARs using reanalyses or models 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 regarding arctic/ high-latitude ARs, we 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 quantifies the magnitude of airborne misrepresentation in sonde-based moisture transport divergence. Correspondingly, our title immediately makes clear that our focus is in the observability.

Nonetheless, we take your suggestion into account in the manuscript. Our conclusions now emphasise the ability of investigating arctic ARs in a more general perspective using CARRA. As listed in the AC1, we promote follow-up studies that attribute dynamic and thermodynamic conditions to the AR characteristics.

Modifications (Line 716ff) : "[…] as we include a large variability of synoptic AR patterns but a small sample, we propose statistics with a larger number of AR events. The statistics can improve our understanding of the moisture transport divergence pattern in arctic ARs and attribute it to the dynamic and thermodynamic atmospheric conditions. Here, CARRA represents a very suitable reanalysis framework for this purpose in follow-up studies. Again, we encourage the use of the higher vertical resolution of the model levels rather than our chosen pressure levels, although sufficient for initial estimates. "

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 a): We restructured our introduction in this way (see AC1 above). We included 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). Please find detailed manuscript modifications in the AC1 above (especially for Section 3 and 4). In compliance with the remarks from Referee 1, we elaborated 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 for the presentation of our arctic AR cases with manifolded discussion of the synoptic conditions causing AR outbreak to the Arctic (see AC1, Sect. 2). In Sect 3.1, we compared the arctic AR-IVT shapes in more detail with those from mid-latitudes

Modifications (Line 301ff): "We find that the arctic ARs are not substantially narrower than the AR widths of global climatology (Guan and Waliser, 2015) and observed mid-latitudes events (Cobb et al., 2021a). Flight planning should therefore consider cross-section distances of about 500-1000 km, similar to mid-latitude ARs. However, this only applies if the legs are not restricted to regions with IVT > 250 kg $m^{-1}s^{-1}$, which is a widely used threshold for mid-latitude ARs (e. g. Ralph et al., 2019). In contrast, the maximum IVT for the arctic events is roughly half as high as the majority of mid-latitude ARs from airborne studies in Cobb et al. (2021a). Moreover, the IVT magnitudes strongly differ between our cases and synoptic conditions. The strongest ARs, with IVT_{max} exceeding 500 kg $m^{-1}s^{-1}$ are found for intense Greenland troughs, while the ARs are weaker along the Siberian pathway (see also Fig. 1). If we compare our ARs with those of other arctic case studies (e. g. Viceto et al., 2022), we are looking at rather strong ARs."

Response b): 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 enlarged and concretized the comparison to mid-latitude based studies. You can find concrete examples given in the AC1 above (e.g. referring to Sect 2.2, 3.1, 3.4, 4.1, 4.2). In particular, the modifications include more analysis of the phenomenology of arctic ARs in contrast to mid-latitude ARs. By this, we consider the knowledge based on mid-latitude ARs. Nonetheless, we keep our original framing/scientific perspective in principle. Still, we now see a progress of the manuscript in providing more details of general arctic AR characteristics. These details are used to additionally improve our argumentation and discussion in the sonde-based assessment. The first paragraph of the conclusions come back to this point and summarize the arctic AR characteristics.

Modifications (Line 638ff): "This study investigated the characteristics of the moisture transport divergence in arctic Atmospheric Rivers (ARs). We elaborated on conditions

of the moisture transport, i.e. the Integrated Water Vapour Transport (IVT), where the high-resolution CARRA reanalyses formed our representation of IVT variability. We considered nine arctic AR events over the Atlantic pathway to the Arctic ocean in the vicinity of the sea-ice edge from last decade. The IVT values in the AR cores range from 300-600 kg m^{-1} s^{-1}, although the ARs are primarily examined north of their center. We thus classify these AR as rather strong for arctic conditions. While specific humidity mostly remains below 6 g kg^{-1}, we cover AR events indicating the presence of a LLJ with wind speeds higher than 30 m s^{-1}. Still, the bell shape of IVT across the AR strongly varies in between the AR cases. The considered cases cover a large variability and consist of various synoptic pattern (extended troughs, blocking situations, single cyclones) in which the AR are embedded.
Given this variety, we analysed the ARs from an airborne perspective […]"

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 sketched the impact of the reanalysis resolution on the arctic AR structure in more detail in Sect. 3.1 and referred to the current study of Viceto et al. (2022) in which they conducted a reanalysis comparison in a case study of arctic ARs. We included two parts:
Modifications (Line 295ff): "[…] we recognise the bell-shaped IVT from both, CARRA and forcing ERA5. Within the cross-section centre which we declare as the AR core in Sect. 2.5, CARRA, however, shows stronger moisture transport with a more pronounced IV T maximum > 500 kg $m^{-1}s^{-1}$. Moreover, CARRA resolves more small-scale structures of the AR moisture transport. In particular, CARRA increases the cross-section variability for this case."

Modifications Line (309ff): "[…] Viceto et al. (2022) documented the improved representation of arctic AR characteristics in ERA5 against coarser reanalysis data. In our comparison of CARRA with ERA5, the location and horizontal pattern of the ARs agree quite well (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 IV T 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: 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 (instantaneous snapshot).
Current methods to derive divergence from airborne soundings require atmospheric stationarity (e.g. Bony and Stevens, 2019), which can only be idealized in observations. To circumvent this issue, Norris et al. (2020) conducted a time-to-space adjustment of their sonde profiles. Our study aims 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 recommendation is very useful 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.
Modifications: no changes made

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 a suitable guideline throughout our manuscript. Under consideration of the remarks from Referee 1, the motivation improved unravelling and identifying our key questions. The synthesis of our answers now has a more precise focus on implications for future airborne measurement strategies.
Modifications: see Responses AC1

Minor

Line 24 – flood may not be the best word choice here, please revisit ("affect"?)
Response: We rephrased the first sentence and included a concise definition of Atmospheric Rivers (ARs):
Modifications (Line 24f): see specification in AC1

Figure 1, Figure 4: locate us in space with lat/lon
Response/Modification (Fig. 1 & 5 [old 4]): we added lat/lon grid accordingly

Figure 3 – suggest including a box in (a) to illustrate where the box in (b) comes from.
Response/Modifications: We included a slight rectangle in the 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 a): 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).
Modifications (Line356f), we reformulated: "Still, we emphasis that a minimum sounding spacing of 100-150 km has to be targeted for arctic ARs,[…]"

Response b): This corresponds to 4-8 dropsondes for most of the AR widths in the range of 400-800 km. However in the conclusions we added that 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 maximum 100 km.
Modifications (Line 664ff) we added:" Larger AR width is not necessarily associated with higher IVT variability and maximum IVT is more correlated to IVT variability. The planning of sonde releases should thus rely on the steepness of IVT along the cross-section. "

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/Modifications: X-axis is changed to spatial intervals. Further information in AC1.

Line 268 – isn't this larger difference in q expected given the colder air?
Response/Modifications: Yes, it is not surprising. We now constrain on the comparison to other arctic ARs and reformulated the paragraph:
(Line 366ff): "Through the entire troposphere, q remains below 5 g kg^{-1} in our arctic ARs. The vertical moisture characteristics in Fig. 8a) resemble soundings of arctic early

summer ARs at Ny-Alesund demonstrated in Viceto et al. (2022) who showed q values up to 5 g kg^{-1}. However, the winds in our AR cross-sections (Fig. 8) are roughly twice as strong as given in the case study of Viceto et al. (2022). Note that the ground-based station from which Viceto et al. (2022) depicted soundings were basically located at the outflow edge of the AR (with IVT ≤ 250 kgm−1s−1) on the Luv side. Easterly winds were orographically slowed down by the massif of Svalbard. In this sense, the marine arctic ARs we consider are undisturbed. This enables stronger winds whose magnitude is rather comparable to mid-latitude AR conditions."

If the AR is more moist or more windy, does that affect the spacing requirements to fully capture the structure?

Response: From our sample, we cannot unambiguously specify that windier ARs requires more dropsondes than moister ARs or vice-versa. But as 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. Still in AR cases, where strong AR centers approach the sea-ice, we expect rising importance of the wind variability. Upcoming studies could investigate this in more detail in a larger sample.

Modifications (Line724ff), we added in the conclusions: **"As our results are mainly based on corridors in the AR exit region, we strongly recommend extending our uncertainty assessment to other AR regions and expect the role of winds and mass convergence to increase in strong AR centers."**

Line 323 – constant winds in time or in space? Can you refer to one of your figures here?

Response: Here, we spoke of the winds along the cross-sections. We rephrased the corresponding statement as follows:

Modification (Line 384ff): "While strong moisture transport in AR3 originates from overall strong winds, moisture varies strongly and seemingly dominates the moisture transport variability (Fig. 8 b). Hence, we hypothesise that in strong arctic ARs with intense winds, moisture variability primarily steers IVT variability and leads to the bell-shaped IVT cross-section pattern depicted in Sect. 3.1"

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.

Modifications (caption Figure 14): We updated the part of the Figure caption: **"Values specify both components (ADV , CONV) for all frontal AR sectors (colour-coded)."**

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 conducted careful cross-reads to assure clarity and readability, and correctness in grammar and word choice.

Modifications: see documented changes

Line 214 – suggest changing "infer" to "investigate"

Response/Modification (Line 293): We changed the wording accordingly.

Line 219 – suggest rephrase "arises the question, how" to "raises the question whether".

Response/Modification: Due to the restructuring of the paragraph, the corresponding sentence was deleted.

Line 264 – suggest rephrase "contributes to IVT with roughly 50%" to "contains roughly 50% of the IVT magnitude"

Response/Modifications (Line 364): We changed it accordingly

Line 265 – remove “even”
Response/Modification (Line 365): removed

Line 321 – suggest rephrase “are little coherent” to “exhibit little coherence”
Response/Modifications (Line 455): We reformulated it accordingly

Line 348 – suggest rephrase “neither it considers” to “it considers neither”
Response/Modification (Line 491): we reformulated it accordingly

Figure 11 – suggest removing “corridors in the” from the caption
Response/Modification: We removed it from the caption

III) Additional author’s changes

Several parts of the manuscript were reformulated or restructured, as seen from above. This section lists some major changes that do not directly result from the comments of the reviewers. We only constrain on some major changes. Here, we do no list all minor changes comprising slight changes in phrasing or slight shortenings. Following the suggestions of the reviewer to carefully rewrite the manuscript, a list of all changes would go beyond the scope of this response list. All other changes can be found in the tracked changes file.

Abstract:

Modifications in bold, inplace:
“This study emulates dropsondes to elucidate how adequately sporadic airborne sondes represent divergence ~~**(convergence)**~~ of moisture transport in arctic Atmospheric Rivers (ARs). The convergence of vertically integrated moisture transport (IVT) plays a crucial role as it favours precipitation that significantly affects arctic sea ice properties. Long range research aircraft can transect ARs and ~~**dropsondes**~~ **drop sondes to** determine their IVT divergence. ~~**However, a limited number of sondes may deteriorate the representation of variability and divergence IVT.**~~ In order to assess the representativeness of future sonde-based IVT divergence in arctic ARs, we disentangle errors arising from undersampling by discrete soundings and from the flight duration ~~in order to assess the representativeness of future sonde-based IV T divergence in arctic ARs.~~
Our synthetic study uses CARRA reanalyses to set up an idealised scenario for airborne AR observations. For nine arctic spring ARs, we mimic flights transecting each AR in CARRA and emulate sonde-based IVT representation by picking single vertical profiles. The emulation quantifies IVT divergence observability by two approaches. First, sonde-based IVT and its divergence are compared to the continuous IVT interpolated onto the flight cross-section. The comparison specifies uncertainties of discrete sonde-based IVT variability and divergence. Second, we determine how temporal AR evolution affects IVT divergence values by contrasting time-propagating sonde-based values with the divergence based on instantaneous snapshots.
For our arctic AR cross-sections, we find that ~~**moisture transport variability contributes to less than 10% to its lateral mean**~~ **coherent wind and moisture variability contribute by less than 10 % to the total transport**~~**, while wind and moisture variability individually are higher**~~**.** Both quantities ~~**can be uncorrelated**~~ **are uncorrelated to a great extent** ~~**and do not consistently exhibit a coherent pattern**~~. Moisture turns out as the more **variable** ~~**varying**~~ quantity. We show that sounding spacing greater than 100 km results in errors greater than 10 % of the total IVT along AR cross-sections. For IVT divergence, the arctic ARs exhibit similar **differences** ~~gradients~~ in moisture advection and mass convergence across the embedded front as mid-latitude ARs, but we identify moisture advection being dominant. **Overall,** we ~~overall~~ confirm their observability with an uncertainty **of around 25-50 % using** ~~lower than by~~ a sequence of at least seven sondes per cross-section. Rather than sonde undersampling, it is the temporal AR evolution over the flight duration that leads to high~~er~~ deviations in divergence components. Dedicated planning of sonde-based IVT divergence purposes should not only involve sonde positioning but rather pursue optimizing the flight duration. Our benchmarks quantify sonde-based uncertainties as a prerequisite to be used for future airborne moisture budget closure in arctic ARs.

Divergence

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 (updated Figure 13-16) have changed moderately. The following, you find the updated figures, alongside a specification of differences to the preprint results. Bullet points highlight major differences to the preprint version. We reserve the right to insert here all the sub-chapters that have been rewritten for the sake of brevity.

4.2 Sonde-based divergence and its representativeness

Erratum modifications:

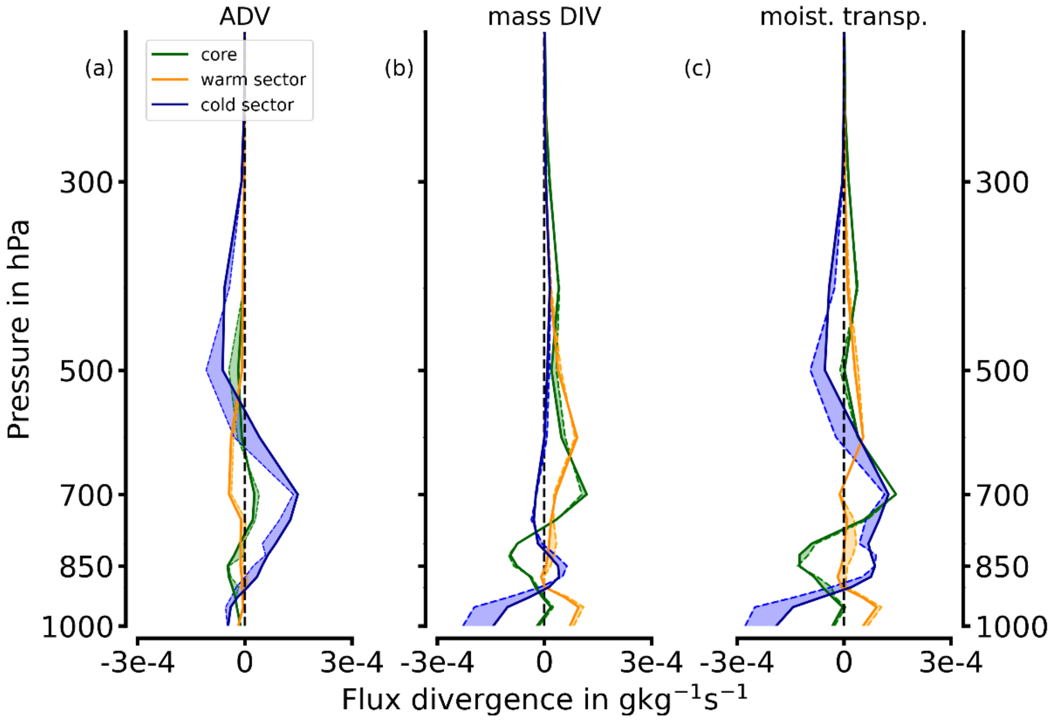

Figure 13: Vertical contributions from *ADV* (a) and *CONV* (b) to moisture transport divergence (c) for the frontal sectors in AR3. Bold lines represent the continuous AR representation while dashed lines depict the sonde-based representation with deviations as shadings.

Changes to preprint results:

- Slightly smaller magnitudes in all components
- warm sector and core values became more positive (less moisture advection and less mass convergence). In particular, the warm sector became rather divergent (Fig. 12c).
- Low-level mass convergence in the cold-sector (exhibited divergence before).

Explanations: Before, we did not consider the u and v components of the wind separately. This directionality, in turn, substantially affects the results. Since the winds are partly elongated with respect to the moisture pattern, we find relevant contributions of cross-section parallel gradients (e.g. in $u \cdot \frac{\delta q}{\delta x}$ and $q \cdot \frac{\delta u}{\delta x}$), that were not pronounced in the previous approach. The current dominant post-frontal mass convergence results from strong changes in wind direction and superimposes rather weak changes in wind speed.

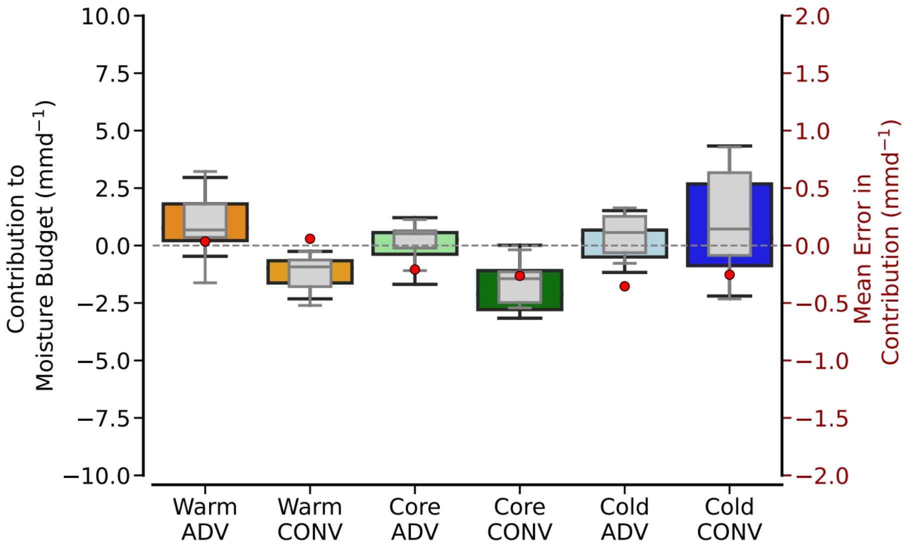

Figure 13: Box plot of moisture transport divergence contributions to daily moisture budget for all nine ARs. Values specify both components (ADV, CONV) for all frontal sectors (colour-coded). The continuous AR representation (coloured box-whiskers) is compared to sonde-based values (grey box-whiskers). The boxes refer to quartiles and horizontal lines specify the respective mean.

Changes to preprint results:

- Smaller magnitudes in moisture budget contributions than before
- Less frontal gradient, meaning less positive contribution in the pre-frontal sector and less negative contribution in the post-frontal sector
- Mass convergence does not exhibit a clear gradient along the front. In particular, the post-frontal sector now shows the strongest mass convergence against all the other sectors (before divergent).

We updated the text in Sect. 4.2, accordingly. To account for the findings of related work in a more concise way, we distinguish the paragraphs that describe our results from the respective discussions referring to mid-latitude statistics given in Guan et al. 2020. This literature comparison is enlarged against the preprint version. Surprising findings, such as the predominant mass divergence in the core are carved out.

Like in Section 4, the divergence results for the instantaneous perspective have changed, causing modified figures. Both figures are displayed here equivalently.

5 Sonde-based divergence and its representativeness

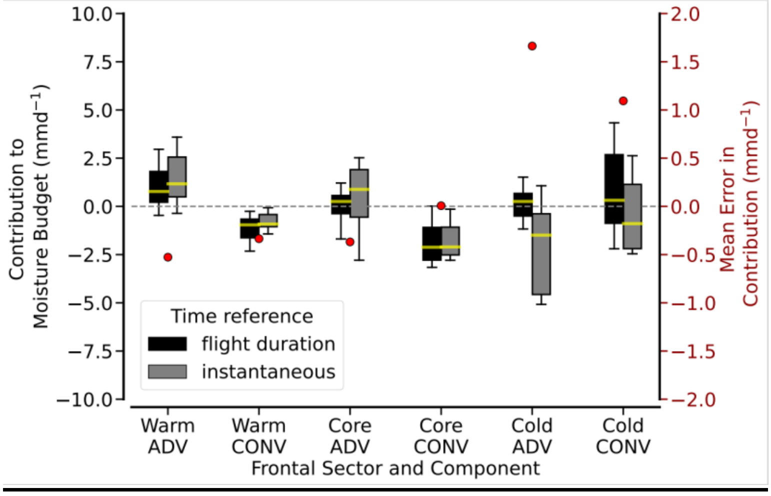

Figure 15: Comparison of divergence component contributions to daily moisture budget from spatially continuous AR representation referring to either evolving flight values (non-instantaneous) or to the values for the centered hour (instantaneous). Values are given for each frontal sector. Black error bars are identical to the coloured boxes in Fig. 14. Grey values represent centered hour-based values. Note that for easy comparison, we here kept the legend entries equivalent to the preprint although slightly renamed in the revised manuscript.

Changes to preprint results:

- Instantaneous whiskers follow the modified frontal tendencies (smaller magnitudes and weaker gradients along the front)
- Mean errors in contribution (red-dots are less affected) by updated divergence calculations the post-frontal sector
- Highest mean error in cold sector advection remains. Robust dry advection visible in instantaneous view on post-frontal sector

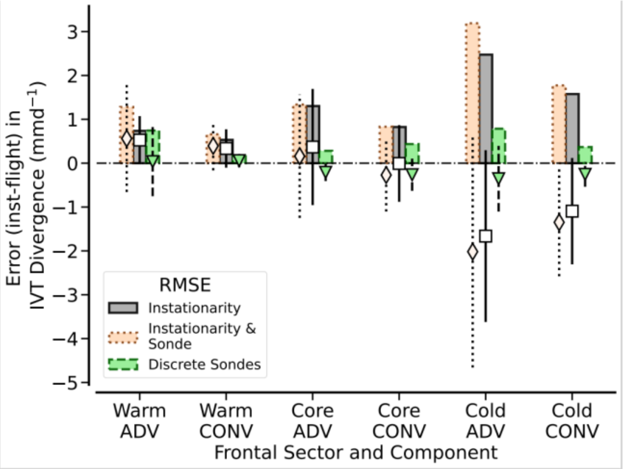

Figure 16: Total sonde error (orange) and individual errors by only discrete sondes (green) and by non-instantaneous sampling (grey) for daily IVT divergence in each frontal sector and divergence component (Eq.). For all AR cross-sections, positive bars indicate the root-mean square error while error markers and lines depict mean errors in combination with their

standard deviations. Note that for easy comparison, we here kept the legend entries equivalent to the preprint although slightly renamed in the revised manuscript.

Changes to preprint results:

- Minor changes in magnitudes
- Equivalent key messages: Non-instationarity counts more than sounding frequency for the sonde-based misrepresentation of moisture transport divergence

We updated the text in Sect. 5, accordingly. The structure aligns to Section 4.2, where we distinguished the paragraphs in a description of the results followed by respective discussions referring to mid-latitude statistics given. This literature comparison is enlarged against the preprint version.