Response to reviewers – "Moisture pathways: a unifying definition for monsoon air streams, atmospheric rivers, and warm moist intrusions"

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We sincerely thank Franziska Aemisegger and an anonymous reviewer for the constructive and in-depth review of our work. We are very happy to read that both reviewers found the material to be well-presented, and even more so that we managed to convey what we believe are the novel aspects of our feature detection approach.

In this public response, we focus on the scientific and conceptual issues that were raised and respond to these in a point-by-point manner. Responses to these issues appear below in blue. The remaining minor and technical issues will be answered point by point in the response to the reviewers directly and they will of course also be addressed in the revised manuscript. Thanks for pointing these out!

Reviewer 1 (F. Aemisegger)

1) I have one major concern with the writing, which is related to the disproportionate focus on atmospheric rivers in the introduction and the slight (certainly unwanted) neglect of the existing tropical and subtropical literature. [...]

We sincerely thank you for this comment. We are very happy to read that the reviewer regards our approach to detecting moisture filaments to be more than yet another atmospheric river detection scheme. This is very much the way in which we see the work ourselves.

The work was previously submitted at JGR-A, where the five anonymous reviewers all seem to belong to the atmospheric river community. To address their comments, we unfortunately had to put much more emphasis on the relation of our detection algorithm to atmospheric rivers than we originally intended. We are thus very happy to shift focus away from atmospheric rivers back to the novel aspects of our detection approach. We will happily rework the introduction following the reviewer's recommendations.

We also thank for the additional context on tropical moisture transport. We are happy to extend the discussion on tropical moisture transport axes using the references both reviewers pointed out.

Minor comments

9) L. 90: I don't really understand why you do need to include "IVT absolute magnitude" in your threshold. Initially, while reading up to here, I enthusiastically thought that your method would avoid exactly that. Now why do you introduce —IVT— when filtering out "weak" maxima, nevertheless? Certainly, this is going to remove many moisture transport axes in polar regions. What happens if you omit this and just filter out minima? You get lots of spurious axes? And you cannot filter them out with the minimum length? Do you then get spaghetti-like messy axes? I am very curious about this and would like to understand this better.

Interesting idea. Our approach was inspired from the jet detection algorithm in Spensberger et al. (2017), where we require the wind maximum to be "well-defined". Sharp wind maxima at low wind speeds would generally not be regarded as jets, so there it was natural to have absolute wind speed contribute to the threshold.

Analogous to that reasoning, we do not impose an |IVT|-threshold separately, but only a combination of |IVT| and the shear gradient $\frac{\partial \sigma_{IVT}}{\partial n}$. Removing the |IVT|-contribution from this field would imply: (a) IVT-maxima of intermediate sharpness will be detected also along very weak moisture filaments, (b) somewhat diffuse maxima along very strong moisture filaments might no longer be detected. In addition to detecting a number of moisture features that are irrelevant for weather we might thus also no longer detect some unambiguous atmospheric river cases, for example when a secondary cyclogenesis along a cold front locally messes up the structure of the (otherwise strong) moisture transport.

10) L. 95: It was exactly when thinking about long climate model simulations that I thought that a |IVT|-independent threshold (i.e. one that would just filter out minima) would be very valuable.

We have applied our algorithm to climate model simulations and found the algorithm to work fine without adaptations for simulations with CESM covering the period 1950-2100 (Konstali et al., 2024a). There was unfortunately no preprint available for this work, but it has recently been published. We will thus now be able to include a reference to Konstali et al. (2024a) in the final publication of this manuscript, supporting our claim.

11) L. 107: Is this similar to what is done in front detection? Are there any parallels to front detection schemes in your method that would be worthwhile mentioning?

True, front line detections in principle need to solve the same normalisation issue for their climatologies. However it seems like published front climatologies generally ignore the issue, and only show the (un-normalised) frequency of lines within each grid point (e.g. Jenkner et al., 2010; Berry et al., 2011; Schemm et al., 2015).

The frequencies in these climatologies thus depend on the (local) grid cell size, with double the cell size yielding double the front frequency. This spuriously reduces detection frequencies at high latitudes on a lat-lon grid, and makes it hard to compare climatologies across datasets of varying resolution.

We were not aware of the problem yet in Spensberger et al. (2017) and there also show un-normalised jet detection frequencies. We later solved the issue in Spensberger and Spengler (2020), but the resulting unit of line length per unit area turned out to be causing confusion. Since the we have been using the approach outlined here.

12) L. 119: When looking at your case studies, I note that the features you detect with the moisture transport axes are coherent large-scale phenomena which are of meteorological relevance. Some properties of the detected moisture transport axes also reveal meso-scale features in addition, which are to date not well studied but which are likely relevant for the understanding and adequate prediction of these systems (among others atmospheric rivers) and their impact.

Great, these are exactly the points we would like readers to note in these snapshots! The focus on coherent large-scale features was our motivation to spectrally filter the input vector field. In the revised version we will explicitly refer back to this methodological goal in this paragraph in order to make connection also for less attentive readers. We will then also point out an example mesoscale feature in the snapshots that might be of further interest.

13) L. 127: does this relate to the two types of WCB outflow branches (cyclonic and anticyclonic outflow?) see Heitmann et al. 2024.

Thanks for pointing us to this study. We agree, there is likely a relation between the cyclonic/anticyclonic curvature of the dominant moisture transport traced by our moisture transport axes and the two types of WCB outflow branches documented by Heitmann et al. (2024). It is beyond the scope of this study to investigate the link more systematically, but we will make sure to include a reference to Heitmann et al. (2024) as very relevant context for our observation.

21) Section 5: I find the discussion around the detection of atmospheric rivers very technical and sometimes difficult to follow. The panel d in Figures 5-9 only show a few contours from the existing atmospheric river detection in the climatological plots and the chosen way of illustrating this intercomparison makes it difficult to compare the new method quantitatively with existing ones. If possible, I would separate the evaluation of the method based on a comparison to others from the scientifically interesting discussion of what the new method detects and what we can learn from it about atmospheric river dynamics.

The atmospheric river community focuses on the MERRA-2 reanalysis. Detections for ERA5 are thus unfortunately only available for a few AR detection schemes. We have included all available global AR detection schemes for ERA5 in our analysis.

We realise the way we explained the detection rates for the global AR detections was incomplete and thus hard to understand. We previously presented the average detection rate across all available detection algorithms for the given composite. We will in the revised version instead show composites of the median AR detection, i.e. the frequency in which the majority of the available algorithms detect AR conditions.

Figure 1a,b of Lora et al. 2020 illustrate this difference for the global AR detection climatology. We hope this change will make the comparison more to the AR literature more straightforward, and we will make sure to explain in detail how we define the AR composites.

22) L. 262-269: I find this way of approaching the identified tropical phenomena a bit awkward. Indeed, there are more persistent features linked to the Monsoon systems but there are also many transient features such as tropical plumes (Rubin et al. 2007) or tropical moisture exports (Knippertz, 2007), often times these systems are related to Rossby wave breaking and are relevant for extreme precipitation in the subtropics (de Vries, 2021).

We agree, our introduction to tropical MTAs was too much rooted in atmospheric river-thinking. We will rework the introduction to tropical MTAs using the references pointed out by both reviewers. Many thanks for the additional context!

23) L. 286-287: are these barrier winds? What does the direction of transport depend on? Are these relevant questions for forecasting in these regions? And can you see and propose how one could address them by using moisture transport axes?

Given the size of the Himalayas, we would expect the moisture transport to be associated with barrier winds, yes, but we have not conducted a formal analysis of the deformation and pressure patterns to substantiate this interpretation.

The direction of moisture transport along the orography barrier does affect the isotopic composition of rainfall in Northwestern India (Joshi et al., 2023), indicating the direction of transport is important to understand the local water cycle. We are however not aware of forecasting challenges associated with the direction of moisture transport.

27) L. 305 recycling vs. large-scale transport: A large share of moisture in cyclone precipitation is fed through the cyclone feeder airstream and originates from the cold sector of previous cyclones as well as the cyclone-anticyclone interaction zone (see, Papritz et al. 2021). Could moisture transport axes be combined with cyclone masks and tracks to study the cyclone-to-cyclone moisture hand over and multi-cyclone association of intense moisture transport in more detail? What about the temporal evolution of moisture transport axes? Can two subsequent moisture transport axes be related to each other?

It should be possible to address most of the questions using our detections. Specifically, we have in the mean time developed a tracking algorithm for jet axes that will be applicable also for MTAs. So yes, two subsequent MTAs can already be related. We have not combined MTAs and cyclone masks beyond some preliminary tests, but we would expect it rather straightforward to combine these features in a joint analysis.

The main obstacle for answering the reviewer's questions will likely be the attribution of moisture transport to MTAs. After all, MTAs only mark the line of maximum transport, which is not enough to calculate a transport budget. However, some of the ideas of the precipitation attribution work by Konstali et al. (2024a,b) might be suitable to fill this methodological gap.

32) I miss a serious discussion of the caveats of the method in the conclusions and an outlook about which scientific questions could be addressed with this new valuable detection scheme.

We agree, and will add a paragraph on caveats. In our eyes, one of the main caveats becomes apparent in our response to issue 27, with a line detection it is not straightforward to attribute a total moisture transport, whereas for areal detections one can simply integrate over the (AR) mask.

Reviewer 2

Major concern, part I The manuscript represents objective global climatology of moisture transport axes. The paper is well-written and the figures are well designed. The method effectively captures moisture transport outside the tropics, including high latitudes.

My major concern is the moisture transport axes (MTAs) within the deep tropics. Specifically, Fig. 3 shows a high frequency of MTAs in the ITCZ region, which I interpret as moisture transport along the ITCZ from east to west. As far as I understand, the ITCZ signifies moisture convergence driven by surface trade winds, typically not organized into distinct filaments. In this instance, the method identifies convergence into the ITCZ as a peak in transport and creates an impression of moisture transport along the axis, not into the axis.

In Supplements, the authors show an alternative method based on normalised water vapour transport. This method gives similar results in extratropics but does not detect ITCZ as an MTA; therefore, in my view, it is better suited for the identification of MTAs. Alternatively, separating MTAs into two types, e.g., dominated by transport along the axis vs transport into the axis or dominated by advection vs water content, might help avoid confusion.

We agree with the reviewer that we detect a relatively large number of MTAs in the deep tropics which might not be desirable for all applications. However, we want to point out that the detection rate in the deep tropics is still only 20-30% in the Tropical Pacific and less in the Tropical Atlantic. In contrast to moisture convergence, MTAs in the deep tropics are thus far from a permanent feature. For example, the broad region of moisture transport across the Tropical Atlantic in Fig. 2g,h is not detected as an MTA because it lacks a clear maximum.

We have had long discussions both internally and with the reviewers of a previous submission of this work at JGR-A on how to include the normalised detections. In the end we settled on keeping the analysis as a supplement, because, as the reviewer points out, this step might be useful for some tropical applications. At the same time it is an unnecessary complication involving unnecessary choices without benefits for the mid-latitudes and potentially more spurious detections at high latitudes. We feel we thus have achieved a reasonable good compromise.

Finally, thanks for the suggestion to differentiate between wet and windy MTAs. We like the suggestion and might follow up on the idea in a subsequent publication. For the present work, we would like to point the reviewer to the two-dimensional histograms in Fig 4, where panel (a) indeed shows a bimodal distribution of TCWV with one peak each representing tropical and extratropical MTAs. The bi-modality is however clearer in latitude (histogram on top of Fig 4a); for the sole purpose of distinguishing tropical from extratropical MTAs, a simple latitude threshold would thus yield a more precise separation than a separation of wet and windy rivers through a threshold in TCWV.

Major comment, part II Furthermore, the authors assert that the method is well-suited for monsoons based on good performance in India and West Africa. However, it appears that, e.g., the Australian monsoon, which brings moisture toward the north of the Australian continent in January-March/April, is not explicitly represented. It may be that moisture transport in this region is not organised in filaments. If this is the case, discussing this nuance in the manuscript could provide a more comprehensive view of the method's applicability across different monsoon systems.

Thanks for pointing out this gap in our analysis, we include the MTA climatology for January-March around Australia as Figure 1 in this document. During the monsoon season, MTAs are detected for about 10-25% of the time steps over large parts Northern Australia. In contrast, detection rates in the region during southern winter (DJF) are generally below 2.5% (Fig. 3c in the manuscript). We thus do see the Australian monsoon with our detections, but admittedly considerably less prominent than its Indian counterpart. We will mention the results of this analysis in the revised manuscript.

Major comment, part III Finally, it would be good to cite the recently published paper (Konstali et al. 2024) that utilises MTAs described in this study. Even though Konstali et al. (2024) cite the pre-print of the manuscript under review submitted to another journal, it would be worthwhile adding a citation of Konstali et al. (2024) in this manuscript highlighting how MTAs contribute to rainfall in different parts of the globe. Following the approach outlined in Konstali et al. (2024), it may be valuable to investigate how frequently MTAs are linked with cyclones and/or fronts, especially in light of findings by Spensberger and Spengler (2018), which demonstrated that heat and moisture transport can be effectively utilised for classification of fronts. Integrating this analysis into Section 5 of the manuscript could significantly enhance the discussion.

We very much agree and will include Konstali et al. (2024) in the revised manuscript. We also very much like the idea to link the MTA detection to the front classification suggested by Spensberger and Sprenger (2018). We will include the front classification in our discussion and we might follow up on that idea in future work. To some degree we do already take this into account in Konstali et al. (2024a,b) by considering MTAs in combination with the Spensberger and Sprenger (2018) frontal volumes and both fronts and MTAs in isolation.

Specific comments

l. 38-42 I would disagree with the statement that 'it is unclear to what extent the concept [of AR] can and should be extended to the subtropics.' Subtropical latitudes are indeed affected by extratropical

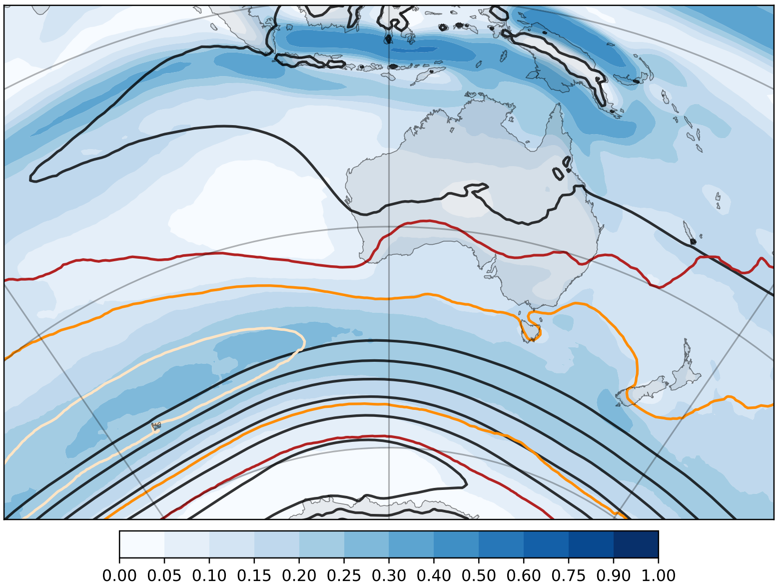

Figure 1: As Fig. 3 in the manuscript, but for January-February-March and focusing on Australia.

weather systems, as you suggested in that paragraph, more often in winter, but also warmer months. Catto et al (2015) show that the highest percentage of cold fronts associated with WCB are found between 20-30degS since the majority of WCBs in their dataset are found equatorward of 40degS. Some papers use the term AR in relation to Australian rainfall (e.g., Rauber et al 2022 (10.1029/2020JD032513), Reid et al. 2020, 2021, 2022). I would argue that subtropics are regions of active ARs as high moisture sources are nearby (Gimeno et al 2021). I think Fig4b of the submitted manuscript supports the idea that moisture is actively transported in the subtropical regions (15-25 deg), depite a relatively low total column water (Fig. 4a). Even though the distribution of axes frequencies at the top of Fig.4 shows a dip in the subtropics, these MTAs are important and might be responsible for extreme rainfall in subtropics and low midlatitudes.

Thanks for bringing this up and for the additional references. We were aware of some work on subtropical ARs, but not of the extent to which the AR concept has already been transferred to the low latitudes. In the light of comments from both reviewers, we will rework our framing of tropical MTAs, both with respect to the introduction and the first paragraphs of section 7.

We agree with the reviewer, Fig 4b shows that typical IVT values do not differ substantially between the tropics, subtropics and extratropics with the most frequent value around 300-350 kg/(s m). At the same time, the gap at subtropical latitudes in Fig 4a does not imply low TCWV, but only that MTAs are relatively infrequent at these latitudes. The darkest shading in Fig 4a for 15-20° latitude is around 40-50 kg/m^2.

l.93 A single threshold based on the global average is potentially biased towards low latitudes with higher moisture content and, therefore, contradicts the idea of avoiding thresholds that you postulated at the very beginning.

We disagree. The single threshold is for a metric taking into account the sharpness of the IVT maximum ($\frac{\partial \sigma_{IVT}}{\partial n}$) and the absolute IVT magnitude |IVT|. By combining these two components into one threshold, we do both detect relatively broad maxima at high absolute IVT as well as narrow and pronounced IVT maxima nearly irrespective of the absolute IVT magnitude. Removing the contribution from |IVT|, as reviewer 1 suggests, would have the following two (generally undesirable) consequences: (a) IVT-maxima of intermediate sharpness will be detected also along very weak moisture filaments, (b) somewhat diffuse maxima along very strong moisture filaments might no longer be detected. In addition to detecting a number of moisture features that are irrelevant for weather, we might thus also no longer detect some unambiguous atmospheric river cases, for example when a secondary cyclogenesis along a cold front locally messes up the structure of the (otherwise strong) moisture transport.

L.130 In fig. 2d, is the transport away from a cyclone associated with a warm front? It seems to be too far from the cyclone centre to be a part of a warm front but maybe it still is.

Yes, that's exactly it. It likely also represents the anticyclonically curving part of the WCB outflow documented in Heitmann et al. (2024; reference through reviewer 1). At the same time, I would have the same hunch as the reviewer and question to what extent the warm sector and cyclone core of this cyclone are still dynamically related. As potentially interesting context, Spensberger and Schemm (2020) consider the same question in more detail for a cyclone making landfall on the Norwegian West Coast. In this case study, orography separated the cyclone core from its warm sector, apparently without affecting the life of the cyclone core too much.

l.135 The moisture transport around a TC does not represent the actual moisture transport which has not been identified as AR by any of the algorithms in ARTMIP-ERA5. Since TCs are relatively rare, their contributions to climatology are small. However, is there a way to remove or improve those axes?

Yes, there are schemes that explicitly remove the moisture transport around TCs. For example, Tempest-Extremes v2.1 explicitly disregards moisture transport within 8° of detected TC cores (Ullrich et al. 2021). If so desired, it would be straightforward to filter our MTAs using a similar criterion. The choice of whether or not to exclude MTAs close to TCs will depend on the application, and we thus do not introduce a TC-filter in the present work.

l. 147 (raised in my general comments) To what extent does ITCZ advect moisture in the zonal direction? My understanding of ITCZ is that it represents the convergence of moisture advected from subtropics. In my view, this advection mostly happens not in filaments. Fig.4 (c,d), tropical moisture axes advect moisture eastward and mainly equatorward.

We think our tropical detection rates in Fig. 3 and tropical snapshot in Fig. 2g,h generally conform with these expectations. Further, Fig. 4c,d show that the moisture transport is clearly more westward than equatorward for tropical MTAs. For more details we refer to our response to the general comment.

l. 200 The peak around 60S in Fig. 4c is weak but can be defined. Can eastward flux at 60 deg lat be associated more with eateries around Antarctica than circulation around the cyclone centre, which usually happens over short distances? I am not sure how this can be objectively measured other than separating the moisture transport into transient and stationary components (which is an interesting avenue, perhaps).

Good point, we will include the suggestion as a second potential explanation for the westward transport around 60° latitude. The number of points comprising this peak is however at least an order of magnitude smaller than the mid-latitude peak in eastward transport, implying that on average less than a tenth of the MTA is pointing westward poleward of a cyclone. Based on our synoptic experience (we detect MTAs in operational ECWMF forecasts), this magnitude does not seem unreasonable.

l.205 I'd recommend showing distributions for tropical and extratropical MTAs separately as they may represent different processes. Also, as far as I understand, this plot shows moisture transport only along the axes, it does not tell you how much moisture is advected within atmospheric rivers as a whole. Therefore, the distribution of moisture transport within atmospheric rivers might be more poleward.

Good idea, thanks for the suggestion! We will in the revised manuscript split the histograms on the sides/top of Figure 4 into tropical and extratropical MTAs.

The reviewer is correct in that the histograms only show the moisture transport at the location of the detected MTA, not for an atmospheric river-like object as a whole. However, the consequence of this discrepancy is generally in the opposite direction as the reviewer suspects. For eastward propagating moisture filaments the transport direction will generally be more zonal than the orientation of the filament, and thus the orientation of the detected MTA. The snapshots in Fig. 2a,e showcase this nicely in that most IVT vectors are veered anticyclonically relative to the moisture filaments following mid-latitude fronts.

l.218 You mention that high latitude ARs/moisture transport is similar to AR in the midlatitudes. In the two Antarctic cases shown in the paper, AR/MTA stretches from the subtropics to the Antarctic coastline. What do you mean by saying that those high-latitude events are 'similar' to their 'midlatitude counterparts'? I read that they are similar but still different (maybe that's not what you meant). In my view, they are created by the same process, i.e., moisture advection associated with a cyclone/frontal circulation that must be the leading cause of ARs formation.

We agree with the reviewer that from a fundamental fluid dynamics-perspective the dynamical origin of MTAs will be the same in the mid- and high latitudes: strain-driven frontogenesis. However, from a weather perspective there are still conceptual differences between the regions. In the mid-latitudes, the strain will predominantly be associated with cyclones and their fronts, whereas in polar regions the palette of weather systems is a bit more diverse. In addition to cyclones with mid-latitude structure, there are also cold-air outbreak boundaries, polar lows, and tropopause polar vortices that all can be associated with frontogenetic strain in the flow field leading to polar MTAs. In the light of this larger conceptual diversity of polar weather, our formulation seems appropriate.

l.252 My reading of Papritz et al is they explore moisture transport into the Arctic. Can you mention their Figure that shows the extrusion of the warm moist air from the polar region? Also, the statement that the transport around the cyclone centre advects air that is still relatively warm should be supported by temperature analysis. As a side comment, it would be interesting if a similar approach could be applied for heat advection.

Papritz and Dunn-Sigouin do never show the export directly, but only what they call net and total fluxes (throughout all figures). Yet, by systematically considering the differences between net and total moisture imports, they show that not all moisture imported into the Arctic stays there.

We do show anecdotal evidence for our interpretation in Fig. 2c, where air with TCWV well above $20\,\mathrm{kg/m^2}$ recurves around the cyclone's occlusion point and is transported equatorward again. For air to hold that amount of moisture, it must be rather warm by subpolar standards. In the light of this, we don't think it is necessary to back up this side remark by a dedicated analysis.

l.264 Subtropical climate is very variable. In winter, extratropical weather systems are often observed in subtropics, especially in the area below the subtropical jet that increases baroclinicity. In warmer months, extratropical circulation shifts further poleward but fronts are still frequently intruding subtropics. Either frontal circulation or cutoff lows can create a strong moisture advection in the subtropics, particularly in late summer-early autumn. ARs are important for rainfall in South Africa (e.g., Blamey et al 2018), Australia (e.g., Reid et al 2022), subtropical South America (Reis et al. 2022), the Middle East and North Africa (Massoud et al. 2020), Southeast China (Xu et al. 2020 https://doi.org/10.1071/ES19027). The subtropical climate varies a lot from one region to another but there are many subtropical areas for which moisture transport in the form of ARs is critically important as they create extreme rainfall events.

We agree that our introduction to subtropical and tropical MTAs needs to be recast. We will reformulate the introductory paragraphs to this section and extend the discussion using the comments and references provided by both reviewers. Many thanks for suggesting additional relevant context!

l. 292 Can you explain why rainfall associated with this moisture transport remained weak given a close proximity to the ITCZ? (Though it could have been strong in a relative sense in this arid region)

As the reviewer points out, the MTAs in question occur over a very arid region rather than the moist ITCZ. In this region it will generally be even warmer than it is moist, and time-mean subsidence further suppresses convection, condensation and rain formation.

l.313 In Fig. 4c, the occurrence of poleward moisture transport in high latitudes(>60deg) is higher than the equatorward transport, suggesting that more moisture is advected into the polar regions than outside.

We agree, and that is also what we write: "Moisture transport axes thus highlight events with pronounced moisture import into polar regions."

l.321 The moisture transport 'along the straits of the Maritime continent', also mentioned earlier in the manuscript, is interesting. Looking at seasonal rainfall (e.g., Fig 1 in Bukowski et al. 2017, 10.5194/acp-17-4611-2017), I cannot see why the moisture transport axis lies exactly between islands. If it is not an artefact, can it be explained?

Thanks for pointing us to the study of Bukowski et al. 2017. We think the focus of our detections on the straits is not an artefact. Many islands of the maritime content feature high orography, and thus block considerable parts of the moisture transport, which is strongest in the lower troposphere. The straits will thus generally feature a maximum in moisture transport relative to the neighbouring islands, which is detected as an MTA.

Supplement, l. 14 Following Wille et al. and Gorodetskaya et al., I think, moisture transport into high latitudes is very important for polar regions. You say that a lower threshold leads to spurious detections over Antarctica. Did you check if axes that would be identified with a lower threshold were not associated with precipitation over Antarctica and, therefore, could be suspected as spurious?

We did not check, in parts because we were unsure how much we can trust ERA5 precipitation over the Antarctic Ice Sheet. Our judgement that many of these MTAs likely are spurious is instead based on their frequency of occurrence of our normalised MTAs in the polar regions, which far exceeded the AR detection rates of, for example, Wille et al. (2021). We will point this reasoning out more clearly in the revised supplement.

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