

We thank [Reviewer 1](#) for his/her comments and suggestions, which helped to improve the manuscript and to remove ambiguities/misunderstandings. Below we provide point-by-point responses to each comment.

Summary:

This study explores the dynamical linkage between extratropical cyclones (ETCs), warm conveyor belts (WCBs), and atmospheric rivers (ARs) through climatological and composite-based analyses. The authors found that ARs linked to ETCs that overlap with the WCB ascent phase exhibit stronger IVT signals and stronger, more widespread and intense precipitation than ARs not associated with ETC WCBs. They also found that an ARs most intense impacts coincide with an ETC's maximum deepening point. These results hold significant implications for how forecast models handle prediction of the timing and location of AR-related precipitation extremes. Overall, the manuscript is generally well written and structured, save for a series of grammatical/abbreviation usage issues that require attention. Additionally, though the series of methodologies utilized are extensively described, there are instances where some components appear to be missing and additional descriptions are required. Save for the need for minor clarifications of a few points, the author's assertions are well supported by the figures and text. In the opinion of this reviewer, this study adds to the existing body of scientific work in a tangible way, fits within the scope of the journal, and is worthy of publication with the addressing of the significant revisions/comments outlined below.

Major Comments:

1. **AR Detection Methodology:** At the very end of Section 2.2 a new axis identification method is mentioned but not described. AR centroids are also heavily utilized in the composite analyses of Figures 4-7, but no methodology on how these centroids are calculated is presented. Please add descriptions to this section describing how both the AR axis and AR centroid are identified.

Answer: We thank the reviewer for this important suggestion. Both the axis and centroid identification are obtained using the original method developed by Xu et al. (2020). The algorithm identifies the AR axis using a graph framework. The process starts by identifying the boundary of the AR region (black dots in Figure 1). Moisture flux data (from the raw IVT field) is then used to classify boundary points as 'entry' or 'exit' nodes for moisture flow. The optimal path, or axis (light-blue points in Figure 1), is determined by solving a shortest-path problem (using Dijkstra's algorithm) that connects an entry point to an exit point, selecting the path that maximizes the integral of along-edge fluxes. This method produces a physically meaningful, continuous curve that captures the AR's main flow direction. The centroid (pink dot in Figure 1) is calculated as the geographic center of the AR object, weighted by its IVT intensity. This weighted centroid gives more importance to areas with higher moisture transport, providing a center that is influenced by the strength of the feature. This description has been implemented in the revised manuscript, in addition to a re-structuring of Section 2.2 based on a comment from the second reviewer. Figure 1 has been added to the supplementary material (as Figure A1d) to illustrate the axis and centroid identification. Please see the comment below on the same topic.

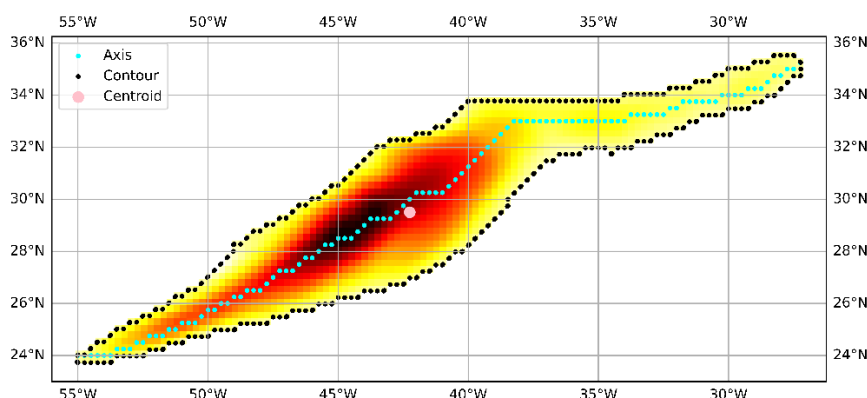


Figure 1 – Identification of the AR's axis, within the AR's area and following the high IVT values. Weighted by the IVT intensity and the shape of the AR, the centroid is defined by the pink dot. This corresponds to Figure A1d in the Supplementary Material.

2. **ETC Tracking Methodology:** There are many different criteria utilized to filter ETCs from the SLP field, some of which come off as arbitrary. For instance, why is the minimum deepening rate set so that only rapidly intensifying cyclones are retained? What happens to the results if non-explosive cyclones are included in the ETC dataset? Also, what percentage of all ETCs fall into the "rapidly intensifying" category? By limiting the

ETC dataset to only those that rapidly intensify, how much of the climatological distribution of ETCs are excluded? Similarly, why is the minimum Laplacian set to the chosen value? A sensitivity analysis on how these criteria affect the ETC climatology is necessary.

Answer: We thank the reviewer for this important comment, as the description of the method was misleading. In particular, we would like to apologize for erroneously including the ‘explosive cyclones’ sentence, which is not correct. Pinto et al., (2009) set the minimum Laplacian thresholds ($\geq 0.6 \text{ hPa}/(\text{degree latitude})^2$ at least once during its lifecycle), the minimum deepening rate of $0.3 \text{ hPa}/(\text{degree latitude})^2$ over 24h and the minimum travel distance of 1000km to remove non-synoptic relevant systems (e.g. semi-stationary heat lows). All these thresholds are comparatively low to warrant a full cyclone climatology also in marginal areas (e.g. the Mediterranean Basin; see also Pinto et al., 2005). Thus, the cyclone database is appropriate to compare with the AR database.

3. AR-ETC Association Methodology: As with the ETC tracking criteria, no basis is given for why 2000 km (and then 4000 km) is chosen as the radius for AR-ETC association. What is the underlying rationale for how these distance criteria are chosen and what is the sensitivity of the resulting ETC-AR association percentage to different radii?

Answer: Zhang et al. 2019 and Guo et al. 2020 systematically quantified the distance between AR centroids and their associated ETC centers across the northern hemisphere, finding that the distance between the two systems varies from ~300 to >2000 km (in Zhang et al. (2019)) and from 500 to 1500km (in Guo et al. (2020)). Based on this, the former searched from an ETC around a 2500km box from the AR’s centroid, and the latter at a 30° distance (~3300 kms). To note that while Guo et al. 2020 look at both northern and southern hemispheres, Zhang et al. 2019 only analyzed the AR-ETC distances on the North Pacific/U.S. West Coast. As such, we chose the primary radius of 2000 km. The secondary radius of 4000km is applied only when no ETC is found within 2000km. This two-step approach accounts for two specific scenarios: (i) decaying ARs where the associated ETC has weakened or moved rapidly poleward, and (ii) very large, occluded cyclones where the AR may be positioned further from the center than in the mature phase. This is applied to our analysis by adding the condition that the AR needs to be within 2000km from the ETC at least once during its lifecycle. A good example is the case study presented on section 3.2, where the AR is located closer to the ETC as it forms, but as it develops it starts to move eastward, farther from the ETC. The AR is still associated with the same ETC, but its distance increases. Of the 99.2% of ARs associated with ETCs, 95% of the time frames are found within 2000km from the associated ETC. The remaining 5% of the time frames of ARs require the 4000 km radius, corresponding in general to the later stages of cyclone development when the warm sector and the AR are located very far from the cyclone core (the AR moves eastward away from the ETC as the system matures).

To account for this, in section 2.5 (‘Assignment of ARs to ETCs’), the second paragraph now yields:

“This procedure successfully associated approximately 99.2% of all ARs events with an ETC. The primary radius of 2000km follows the work of Zhang et al. (2019) and Guo et al. (2020), who systematically quantified the distance between AR centroids and their associated ETC centers across the northern hemisphere, finding that the distance between the two systems vary from ~300 to >2000 km (in Zhang et al. 2019) and from 500 to 1500 km (in Guo et al. 2020). Based on this, the former searched for an ETC around a 2500kmx2500km box from the AR’s centroid, and the latter at a 30° distance. As such, we chose the primary radius of 2000km. The secondary radius of 4000km is applied only when no ETC is found within 2000km. This two-step approach accounts for two specific scenarios: (i) decaying ARs where the associated ETC has weakened or moved rapidly poleward, and (ii) very large, occluded cyclones where the AR may be positioned further from the center than in the mature phase. This is applied to our analysis by adding the condition that the AR needs to be within 2000km from the ETC at least once during its lifecycle. The 2000km radius successfully associated approximately 95% of ARs with an ETC while the remaining 5% of ARs require the 4000 km radius (distribution shown in Figure A2). ”

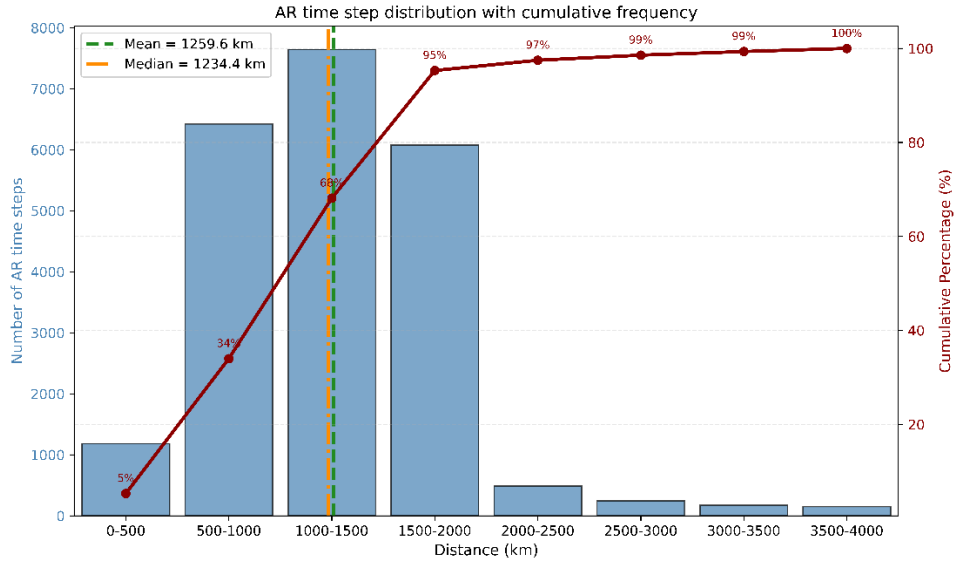


Figure 2 – Distribution of the distances between each AR object and the associated ETC (each 500 km). 95% of the time frames are within 2000km, leaving only 5% between 2000–4000 km. These correspond to 21332 and 1051 AR objects, respectively.

4. Abbreviation Usage: Throughout the manuscript, within both the main text and figure captions, there are multiple instances where an already defined, abbreviated term is re-defined. Please only define each abbreviated term **once** with the first usage, then use the abbreviated term at all subsequent instances.

Answer: We have carefully review the entire manuscript, including all figure captions, to ensure that each abbreviation is defined only at its first occurrence. This correction is applied systematically throughout the revised manuscript and we have also address the redundant definitions noted by the reviewer in the figure captions.

5. Grammar: Throughout the manuscript there are many mismatched usages of verb suffixes. For example, on line 11 “understand” is used where “understanding” would be appropriate, on line 113 “follow” is used where “follows” would be appropriate, and so on. Please review the manuscript to improve the grammar, including the additional instances mentioned in the minor comments.

Answer: We have perform a comprehensive grammatical revision of the entire manuscript. Changes have been made accordingly within the revised manuscript.

Minor Comments:

1. Lines 140-147: Including an example step-by-step figure of the AR detection algorithm here would be very informative, as it is a bit hard to visualize/follow from just the text description.

Answer: To address this and the first comment by the reviewer, we added a new schematic figure (Figure A1 in the Supplementary Material, also shown below), illustrating the three IVT fields used in the AR detection (the IPART detection steps), and the axis identification. In addition, there is a comment from the other reviewer to change the structure of the IPART’s explanation (section 2.2). Accordingly, we have reorganize the IPART’s explanation section to:

“For the detection of AR events, we have implemented and adapted the global AR tracking method developed by Xu et al. (2020) and widely used in recent years (e.g., Fernández-Alvarez et al. 2023; Ferreira et al. 2025a, 2025b). The detection algorithm is based on thresholds at the spatiotemporal scale of ARs and is independent of the IVT thresholds. Unlike conventional methods, IPART (image-processing-based atmospheric river tracking method) is less dependent on magnitude thresholds, detecting ARs based on their spatial ‘spikiness’ rather than absolute moisture values. This approach is particularly advantageous because it identifies ARs as transient moisture anomalies superimposed on the climatological moisture field, making the detection less sensitive to regional variations in background moisture – a critical feature when comparing events across different seasons and regions. This is achieved by the use of the ‘Top Hat by Reconstruction’ technique (Vincent, 1993), which involves subtracting a greyscale reconstruction by dilation image from the original image (Figure A1). This greyscale reconstruction by dilation image is the background IVT content, and the original image is the non-negative IVT distribution. The latter refers to the raw/total observed IVT field (Figure A1a), from which the smoothed large-scale environmental background (the former, Figure A1b) is subtracted to isolate the transient IVT anomalies (Figure A1c), in which the ARs are searched for. A threshold of 200 kg m⁻¹ s⁻¹ is applied

to the anomaly field, and for each region the standard criteria for AR detection (length ≥ 2000 km; width < 1000 km; length/width ratio > 2) are implemented. More details on this method can be found in Xu et al. (2020).

Additionally, in order to exclude tropical cyclones from the analysis, we apply both a circularity criterion with a maximum value of 0.5 (following the work of Mahto et al. 2023) and a minimum value of 1000 km to the distance between the first and last points of the AR axis, ensuring that the feature is a long, filamentary plume, distinct from the closed circulation typical of tropical cyclones. Here, an AR object corresponds to an AR detected at a timestep and an AR event as the entire lifecycle tracking. A key advantage of IPART is that it is more robust for detecting ARs in both midlatitude and polar systems, without changing settings, and in a warming climate where atmospheric moisture levels are expected to increase (Lu et al. 2025). The filtering process is relatively insensitive to the size/shape of the structuring element, providing greater tolerance to varying water vapor flux intensities. Also, the new axis identification method (developed by Xu et al. 2020) provides a physically correspondent axis that follows major flow directions, stays close to the maximum flux values, handles complex shapes, and never extends out of the AR boundary. For this, the process starts by identifying the boundary of the AR region (Figure A1d). Moisture flux data (from the raw IVT field) is then used to classify boundary points as ‘entry’ or ‘exit’ nodes for moisture flow. The optimal path, or axis (light-blue points in the image below), is determined by solving a shortest-path problem (using Dijkstra’s algorithm) that connects an entry point to an exit point, selecting the path that maximizes the integral of along-edge fluxes. For the centroid identification (pink dot in the image below), used as the central point throughout this study, the geographic center of the AR object, weighted by its intensity, is calculated. This weighted centroid gives more importance to areas with higher moisture transport, providing a center that is influenced by the strength of the feature.”

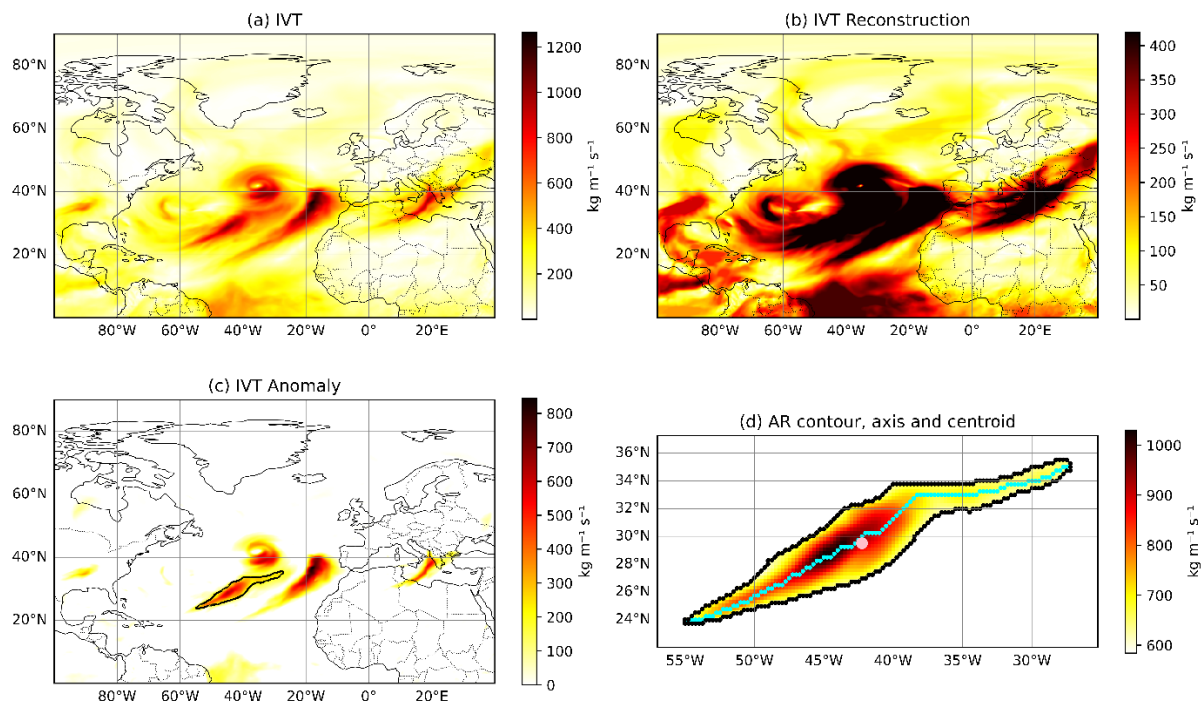


Figure 3 – AR identification process. Using the image-processing method, from the original IVT (image a) the background field is obtained (image b). By subtracting these two fields, we obtain the anomaly (image c) in which ARs are searched for. Image (d) represents the axis identification (light-blue dots) and the centroid location (pink dot). The AR’s contour is represented as black dots.

2. Lines 167-170: This reads like a confusing run-on sentence, please revise for clarity.

Answer: We thank the reviewer for suggesting these improvements. To avoid any confusion, this sentence has been re-written to:

“Trajectories are only considered if first, it ascends in 48h by at least 600hPa and, second, are matched with an ETC (Wernli and Schwerz, 2006) at least once during this 48h period. Based on these criteria, the WCB trajectory is segmented into three phases according to vertical pressure levels: the inflow (below 800 hPa), the ascent (between 800 and 400 hPa), and the outflow (above 400 hPa). The inflow originates from the boundary layer in the warm sector of ETCs, where warm, moist air converges into the cyclone. In the ascent phase, air is carried upward across the cyclone’s warm front, while the outflow phase transports it to the upper troposphere, where it can influence downstream flow.”

3. Line 185: Replace “an” with “its.”

Answer: We have changed accordingly.

4. Line 186: Should be written as “a SLP minima” not “an SLP minima.”

Answer: We have changed accordingly.

5. Line 190: Do you mean “requiring” not “requiting”?

Answer: We have changed accordingly.

6. Line 199: “Measured”, not “measure.”

Answer: We have changed accordingly.

7. Line 210: “Avoid,” not “avoiding.”

Answer: We have changed accordingly.

8. Line 225: Missing the closing parenthesis here.

Answer: Thank you for spotting the typo. It’s now corrected. To avoid any confusion from the reader, we have revised the paragraph to:

“Each AR object was rotated by an angle of $(90^\circ - \theta)$, where θ is the object’s primary directional orientation. This calculation effectively reorients all AR objects to a common west-to-east orientation within the composite framework, aligning their moisture plumes along a standardized longitudinal axis. This transformation is illustrated in Figure 1. For a given timestep, the original fields (Figure 1a) are rotated such that the AR’s primary axis is aligned zonally (west-to-east) within the composite framework (Figure 1b); and.....”

9. Line 240: “Composites,” not “composite.”

Answer: We have changed accordingly.

10. Figure 2e: Presenting this as a percentage (i.e., AR count per year/ETC count per year) instead of just the ETC count might be more informative and provide a stronger basis for your conclusion drawn in line 296.

Answer: We thank the reviewer for this comment. We agree that presenting the data as a percentage is far more informative, as it normalizes for the underlying spatial distribution of cyclogenesis and isolates the true preferential coupling between the two systems. Accordingly, we have replaced Figure 2e as the requested AR/ETC ratio (i.e., AR count per year / ETC count per year). The updated figure still shows a pronounced maximum in the western North Atlantic and off the northwest coast of Europe, with values reaching up to 4.5%, meaning that in these regions, up to 4.5% of all ETCs are co-located with an AR. We have revised the corresponding paragraph (including line 296) to emphasize that this ratio-based view provides a robust basis for our conclusion that the western North Atlantic is the primary region where ETCs are preferentially linked to ARs, rather than simply reflecting the high overall storm frequency there. The revised text is:

“While only about 30.5% of all ETCs have an associated AR, a remarkable 99.2% of detected ARs are linked to an ETC. This underscores that almost every AR in this region is an integral component of a larger synoptic-scale cyclonic system, acting as its primary moisture reservoir. To isolate the preferential coupling between the systems, Figure 2e displays the ratio of ARs to total ETCs. The highest ratios are found in the western North Atlantic and just off the northwest coast of Europe (up to 4.5%), which aligns with our conclusion that ETCs linked to ARs preferentially form directly over the Gulf Stream.”

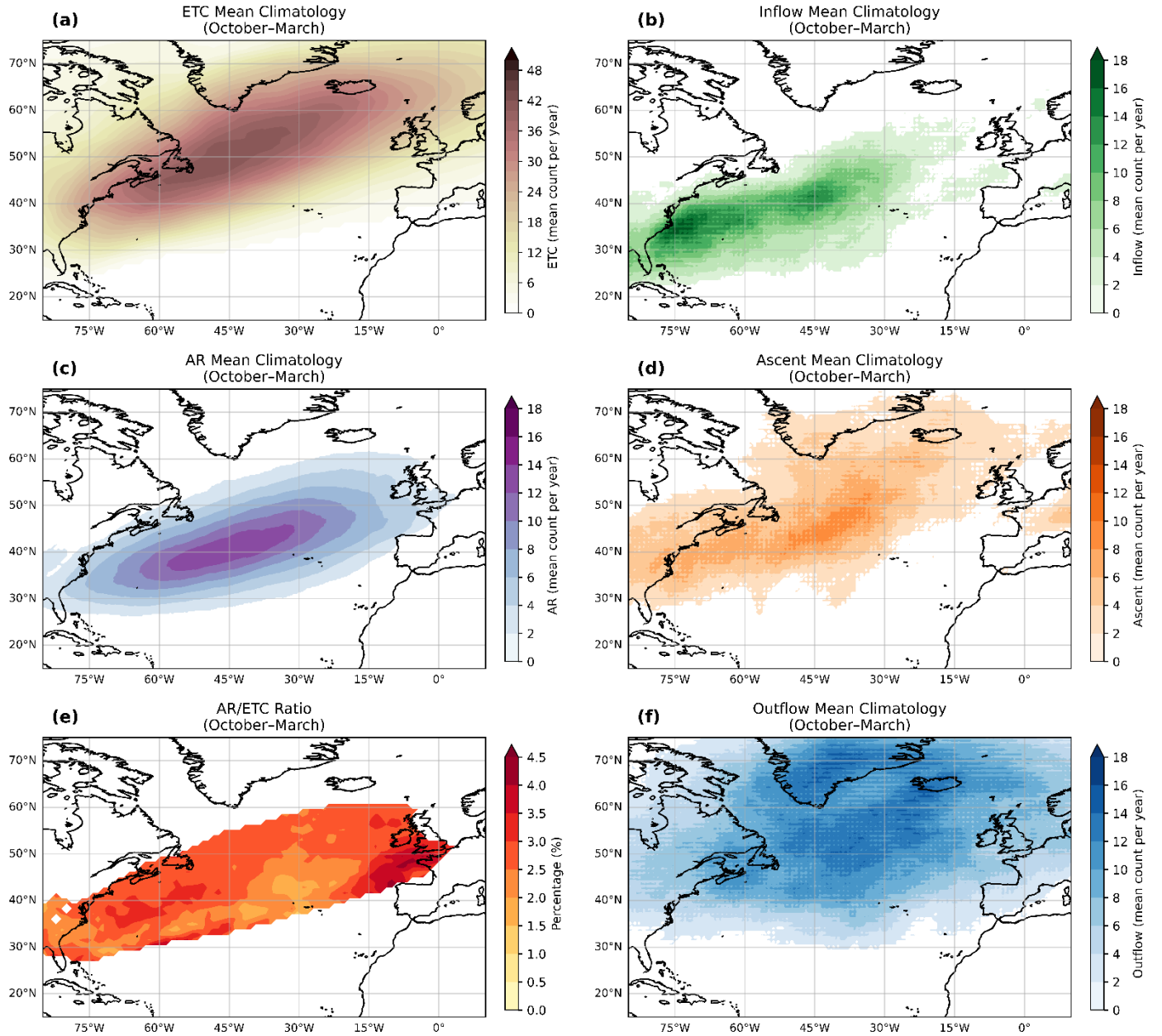


Figure 4 - Extended winter (October-March) climatology (1979-2023) of (a) all ETCs frequency, (b) WCB inflow frequency, (c) AR frequency, (d) WCB ascent frequency, (e) AR/ETC Ratio (AR count per year / ETC count per year), and (f) WCB outflow frequency. Grey line represents the axis of the ETC climatology's distribution showed in (a), for easier orientation.

11. Figure 2 Caption: Remove the following additional text: “Note the coherent spatial pattern from the Gulf Stream region northeastward, with AR and WCB inflow maxima positioned downstream of the primary SST gradient and upstream of the peak ETC and WCB ascent activity.” This type of description doesn’t belong in the caption and is already discussed in Section 3.1.

Answer: We thank the reviewer for suggesting these improvements. We have removed this text from the caption of Figure 2.

12. Figure 3 Caption: Clarify the bold black contour is the AR boundary.

Answer: Caption from Figure 3 states: “Black contours show SLP, with the bold contour indicating the detected AR boundary.” To make the separation clearer, this has been changed to: ‘Thin black contours indicate SLP data, and the bolder black contour, on the bottom images, represent the detected AR boundary.’

13. Line 311: “Coincides”, not “coinciding”.

Answer: We have changed accordingly.

14. Line 312-313: Suggest rewriting as: “The following day (on 6 February, 00UTC, Figure 3e), the WCB ascent and inflow move east with the AR away from the ETC center while the AR intensifies on both moisture content and spatial extent.”

Answer: We have adopted this suggested wording.

15. Line 314: Remove “both.”

Answer: We have changed accordingly.

16. Line 332: Rewrite as, “To note, values...”

Answer: We have changed accordingly.

17. Figure 4 Caption: Specify the grey contours are drawn at 20% intervals.

Answer: We have added: “Grey contours show the relative frequency of AR occurrence (drawn at 20% intervals, from 10% to 90%).”

18. Line 335: “Confirms,” not “confirm.”

Answer: We have changed accordingly.

19. Lines 335-336: If the AR centroid is located at (0,0), wouldn't that make the cyclone also eastward of the centroid? It would be more accurate to state that the cyclone is poleward and westward of the anticyclone.

Answer: We need to keep in mind that these are rotated composites. If we look at Figure 1, we see that, on the non-rotated field, the ETC is located northwestward of the AR centroid. Upon rotation, the ETC is located to the north of the centroid. The main conclusions here are: (1) the proximity of the ETC to the AR; (2) the presence of the AR where the pressure gradient is at its highest (between the cyclone and the anticyclone). However, to not induce the reader in error, we have changed the phrase to:

"...a cyclone situated poleward of the AR centroid (north, in this rotated coordinate system) and an anticyclone to the south and east. In the original (non-rotated) geographical coordinates, this corresponds to the cyclone being located northwest of the AR centroid, consistent with the classical warm-sector positioning of ARs relative to ETCs."

20. Line 351: Do you mean to say centroid here?

Answer: Yes, the origin point corresponds to the centroid of ARs. The sentence has been reformulated to make it clearer, thus where it reads ‘the origin point (0,0)’ it has been changed to ‘at the centroid’ in the revised manuscript.

21. Line 355: Perhaps link this sentence to Figure 5c just after “large-scale ascent”?

Answer: We have changed accordingly.

22. Figure 5 Caption: Specify the range of contour percentages and intervals they are drawn at, as in Figure 4.

Answer: We have added: “Grey contours show the relative frequency of AR occurrence (drawn at 20% intervals, from 10% to 90%).”

23. Many uses of “on” instead of in (e.g., Line 373, 381, etc.).

Answer: We have systematically replace incorrect uses of ‘on’ with ‘in’ throughout the manuscript. A full proofreading has been conducted to catch all such instances.

24. Line 382-384: The middle of this sentence reads very over-complicated, please revise for conciseness and clarity.

Answer: We agree with the reviewer. The sentence has been rephrased to: “The composite results demonstrate that the WCB ascent and AR are not merely co-located, but the former plays a critical role in potentially transforming the intense AR’s moisture transport into an extreme precipitation event.”

25. Lines 404-405: From Figures 6 and 7 it appears the WCB ascent frequency, IVT, and precipitation maxima all peak at MDP and MDP – 12h. At +12h these fields are already beginning to weaken. Please revise.

Answer: We thank the reviewer for this careful observation. We have revised the text to state that the peak occurs at MDP and MDP-12h.

26. Line 425-427: This note would make more sense to be placed earlier around Line 400.

Answer: We have moved this note to the beginning of Section 5, where the composite framework is first presented.

27. Line 430: Is a 1/mm increase truly significant? Perhaps remove that adjective.

Answer: We agree. We have removed “significant” and simply state the numerical change.

28. Lines 491-492: What is being said at the end of this sentence is unclear. Please revise for clarity.

Answer: We agree with the reviewer. Considering this and the other reviewer’s comment, this sentence has been rephrased to: “In ascent-absent cases, precipitation is substantially weaker (with values lower than 5 mm) and forms a diffuse northeastward extent towards the cyclone center. This weak signal likely arises from less efficient mechanisms such as broad slantwise ascent or residual frontal uplift, which lack the focused, enhanced vertical motion characteristic of a WCB”

29. Line 540: Rewrite as “Moreover, ongoing climate change is expected to change both ETC and AR characteristics.”

Answer: We have adopted this wording.

We thank [Reviewer 2](#) for his/her comments and suggestions, which helped to improve the manuscript and to remove ambiguities/misunderstandings. Below we provide point-by-point responses to each comment.

Review of “A composite-based analysis of the dynamical linkage of Atmospheric Rivers, Warm Conveyor Belts, and Extratropical Cyclones” by T. Ferreira et al.

General comments:

In this manuscript, Ferreira et al. presents a comprehensive, composite-based analysis of the relationships between atmospheric rivers, warm conveyor belts, and extratropical cyclones. Overall, this is a well-conceived and highly relevant study. I believe this manuscript has strong potential to make a meaningful contribution to our understanding of mid-latitude weather systems. However, there are a few important points that should be addressed to further improve the quality and presentation of the paper. First, there is a recurring tendency to interweave new results with broad literature discussions, which dilutes the impact of the new findings. I suggest moving these interpretive points to a dedicated discussion section to keep the results section focused. Second, the authors must be careful regarding selection bias: by filtering only for rapidly intensifying cyclones and pre-filtering certain temporal analyses to only include AR-WCB-coupled cases, some conclusions regarding universal coupling are overgeneralized and require more nuanced phrasing. Lastly, there are several instances of contradictory terminology, and, while the paper is generally well-written, a close proofreading is needed to eliminate grammatical errors and typos. I encourage the authors to address these points, which will substantially strengthen the overall clarity and impact of their work.

Answer: We thank the reviewer for these constructive comments. We agree that the interweaving of results with literature discussion can dilute somehow the impact of our new findings. To address this, the results sections has been revised to focus strictly on the objective description of our composite fields and, additionally, a separate discussion section has been created. Regarding the selection bias, we apologize for the wrong explanation of the criteria applied to the composites shown. The 0.3hPa criterion was tested (see comment 6), but the results shown in this study do not account for the application of this criterion to the ETC dataset. Finally, we have conducted a thorough proofreading of the entire manuscript to eliminate grammatical errors, typos, and terminology inconsistencies, addressing all specific instances raised in the minor comments below.

Specific comments:

- 1) References in the introduction: Please add 1–2 references to the original, seminal literature on the conveyor belt model and ARs, supplementing the review by Dacre (2020) and the studies currently cited on line 64. Furthermore, references for the Norwegian Cyclone Model should be added.

Answer: We thank the reviewer for this suggestion. We added the following references:

- i. For the Norwegian Cyclone Model:
 - a. Bjerknes, J., and H. Solberg: Life cycle of cyclones and the polar front theory of atmospheric circulation. *Geophys. Publ.*, 3, 1–18. Available on: https://geofysikk.org/NGF/GeoPub/NGF_GP_Vol03_no1.pdf, 1922. This is cited on line 32, where we discuss the classical cyclone structure.
 - ii. For the conveyor belt model:
 - a. Carlson 1980, already cited in the manuscript on line 47.
 - iii. For the atmospheric rivers:
 - a. Ralph, F. M., Neiman, P. J., and Wick, G. A. Satellite and CALJET Aircraft Observations of Atmospheric Rivers over the Eastern North Pacific Ocean during the Winter of 1997/98. *Monthly Weather Review*, 132(7), 1721–1745. [https://doi.org/10.1175/1520-0493\(2004\)132<1721:SACAOO>2.0.CO;2](https://doi.org/10.1175/1520-0493(2004)132<1721:SACAOO>2.0.CO;2), 2004., which is considered one of the foundational observational studies of ARs. This is added alongside Ralph et al. (2018) on line 64 when introducing AR definitions.
- 2) The exact temporal range (start and end years) of the ERA5 data used for the analysis is absent from the manuscript. Please explicitly state these years in Section 2. Furthermore, if your analysis period extends past

2016, explicitly noting this will help justify the use of ELIAS—highlighting how the machine learning approach allows you to efficiently extend the analysis into recent years without the need to compute WCB trajectories for that timeframe.

Answer: The last paragraph of section 2.1 has been re-written to account for the study period: “The analysis is applied to the entire North Atlantic basin and the western and central regions of Europe, ranging from 100°W to 40°E and 0 to 90 °N, considering only the extended winter season (from October to March) for the period 1979 to 2023.”

- 3) Section 2.2 (AR Detection via IPART): The explanation of the IPART method is scientifically sound, and I appreciate that the authors define what the image components represent (e.g., background vs. transient IVT). However, the technical workflow is somewhat difficult to follow on a first reading because the mathematical/image-processing jargon is introduced before the physical motivation is explained. Consider reordering the narrative flow of this paragraph. If you move the explanation from lines 152–155 (explaining that IPART detects ARs based on spatial “spikiness” rather than absolute magnitude thresholds) to the beginning of the section, it will provide the reader with the necessary physical context before they encounter technical terms like “greyscale reconstruction by dilation”. Additionally, the distinction between “background IVT content” and “non-negative IVT distribution” on line 143 is jargon-heavy and potentially confusing. Please consider explicitly stating that the “non-negative IVT distribution” refers to the raw/total observed IVT field, from which the smoothed large-scale environmental background is subtracted to isolate the transient AR anomalies (if I understood that correctly). This will make the methodology much more intuitive and accessible to a general meteorological audience.

Answer: We thank the reviewer for the comment. To account for these and the comments from the other reviewer, we have reorganized IPART’s explanation section to:

“For the detection of AR events, we have implemented and adapted the global AR tracking method developed by Xu et al. (2020) and widely used in recent years (e.g., Fernández-Alvarez et al. 2023; Ferreira et al. 2025a, 2025b). The detection algorithm is based on thresholds at the spatiotemporal scale of ARs and is independent of the IVT thresholds. Unlike conventional methods, IPART (image-processing-based atmospheric river tracking method) is less dependent on magnitude thresholds, detecting ARs based on their spatial ‘spikiness’ rather than absolute moisture values. This approach is particularly advantageous because it identifies ARs as transient moisture anomalies superimposed on the climatological moisture field, making the detection less sensitive to regional variations in background moisture – a critical feature when comparing events across different seasons and regions. This is achieved by the use of the ‘Top Hat by Reconstruction’ technique (Vincent, 1993), which involves subtracting a greyscale reconstruction by dilation image from the original image (Figure A1, Figure 1 below). This greyscale reconstruction by dilation image is the background IVT content, and the original image is the non-negative IVT distribution. The latter refers to the raw/total observed IVT field (Figure A1a), from which the smoothed large-scale environmental background (the former, Figure A1b) is subtracted to isolate the transient IVT anomalies (Figure A1c), in which the ARs are searched for. A threshold of 200 kg m⁻¹ s⁻¹ is applied to the anomaly field, and for each region the standard criteria for AR detection (length ≥ 2000 km; width < 1000 km; length/width ratio > 2) are implemented. More details on this method can be found in Xu et al. (2020).

Additionally, in order to exclude tropical cyclones from the analysis, we apply both a circularity criterion with a maximum value of 0.5 (following the work of Mahto et al. 2023) and a minimum value of 1000 km to the distance between the first and last points of the AR axis, ensuring that the feature is a long, filamentary plume, distinct from the closed circulation typical of tropical cyclones. Here, an AR object corresponds to an AR detected at a timestep and an AR event as the entire lifecycle tracking. A key advantage of IPART is that it is more robust for detecting ARs in both midlatitude and polar systems, without changing settings, and in a warming climate where atmospheric moisture levels are expected to increase (Lu et al. 2025). The filtering process is relatively insensitive to the size/shape of the structuring element, providing greater tolerance to varying water vapor flux intensities. Also, the new axis identification method (developed by Xu et al. 2020) provides a physically correspondent axis that follows major flow directions, stays close to the maximum flux values, handles complex shapes, and never extends out of the AR boundary. For this, the process starts by identifying the boundary of the AR region (Figure A1d). Moisture flux data (from the raw IVT field) is then used to classify boundary points as ‘entry’ or ‘exit’ nodes for moisture flow. The optimal path, or axis (light-blue points in the image below), is determined by solving a shortest-path problem (using Dijkstra’s algorithm) that connects an entry point to an exit point, selecting the path that maximizes the integral of along-edge fluxes. For the centroid identification (pink dot in the image below), used as the central point throughout this study, the geographic center of the AR object, weighted by its intensity, is calculated. This weighted centroid gives more importance to areas with higher moisture transport, providing a center that is influenced by the strength of the feature.”

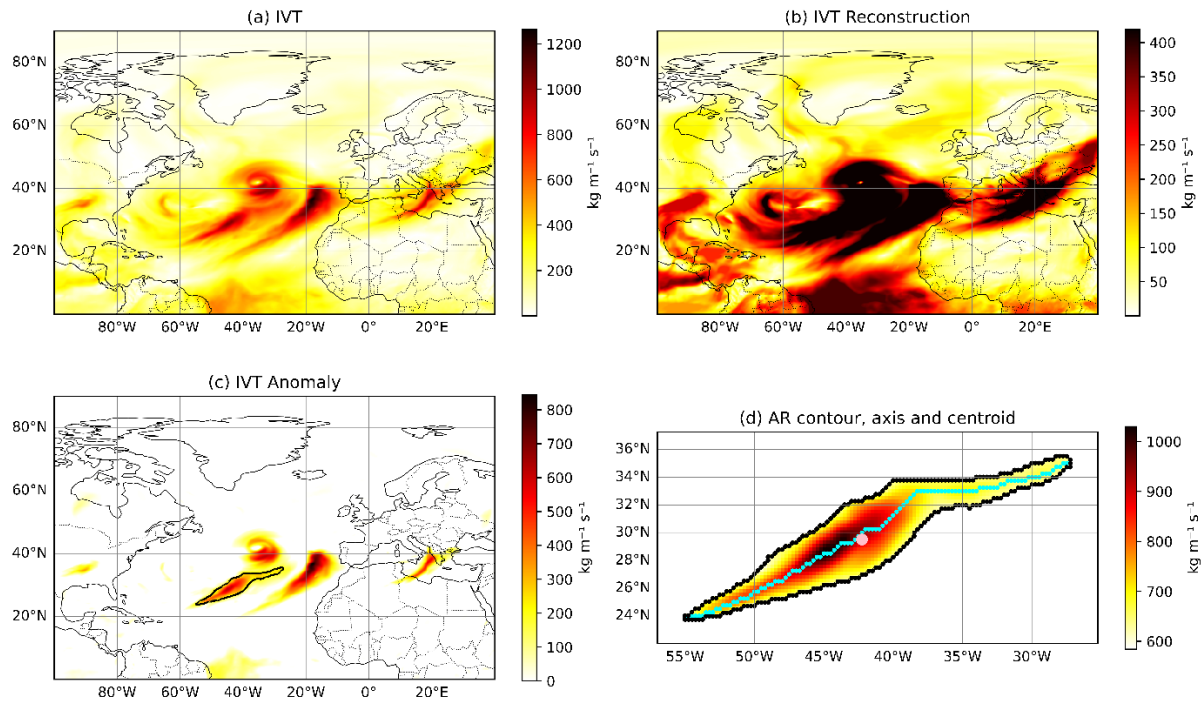


Figure 5 - AR identification process. Using the image-processing method, from the original IVT (image a) the background field is obtained (image b). By subtracting these two fields, we obtain the anomaly (image c) in which ARs are searched for. Image (d) represents the axis identification (light-blue dots) and the centroid location (pink dot). The AR's contour is represented as black dots.

- 4) On line 156, you introduce a “new axis identification method” and list its advantages. However, it is not clear from the text whether this is a novel modification introduced by the authors in this study, or if it is a pre-existing feature of the Xu et al. (2020) IPART algorithm. Please clarify this distinction and briefly explain how this axis is determined.

Answer: The axis identification method used in this study is a pre-existing feature of the IPART algorithm (Xu et al. 2020) and was not modified by the authors. This has been made clearer in the revised manuscript. See comment above for the final version of section 2.2.

- 5) Section 2.3 (WCB Identification via ELIAS): This paragraph is dense and difficult to follow because it interweaves the physical description of WCB stages, the Lagrangian training data, and the machine learning architecture all at once. I suggest splitting this into two shorter paragraphs to improve readability:
 - a. Paragraph 1 (the physical targets): Define what WCB inflow, ascent, and outflow footprints are based on the traditional Lagrangian criteria (e.g., the 600 hPa ascent in 48 hours, and the > 800 hPa, 400-800 hPa, and < 400 hPa vertical layers).
 - b. Paragraph 2 (The ML method): Introduce ELIAS as the Convolutional Neural Network (CNN) tool used to predict these footprints. Briefly explain for a general meteorological audience that the CNN recognizes these spatial patterns using 2D atmospheric fields, and then list the 5 predictors clearly.

Answer: We thank the reviewer for this comment. We agree that we should clarify the ELIAS explanation in the revised manuscript. To account for the other reviewer's comments on this section, a few changes were made to the text. Accordingly, section 2.3 now yields:

“The method ELIAS (EuLerian Identification of Ascending AirStreams), developed by Quinting and Grams (2022), uses convolutional neural networks to predict the conditional probabilities of the WCB inflow, ascent, and outflow footprints. The model was trained on a labelled dataset where the ‘ground truth’ for each WCB stage was defined using Lagrangian trajectories (from Madonna et al. (2014) and extended to 2016 by Sprenger et al. (2017)), computed with the LAGRANTO algorithm (Wernli and Davies, 1997; Sprenger and Wernli, 2015) on a $1^\circ \times 1^\circ$ horizontal grid, using the ERA-Interim dataset. Trajectories are only considered if first, it ascends in 48h by at least 600hPa and, second, are matched with an ETC (Wernli and Schwerz, 2006) at least once during this 48h period. Based on these criteria, the WCB trajectory is segmented into three phases according to vertical pressure levels: the inflow (below 800 hPa), the

ascent (between 800 and 400 hPa), and the outflow (above 400 hPa). The inflow originates from the boundary layer in the warm sector of ETCs, where warm, moist air converges into the cyclone. In the ascent phase, air is carried upward across the cyclone's warm front, while the outflow phase transports it to the upper troposphere, where it can influence downstream flow.

ELIAS employs a convolutional neural network architecture that learns to recognize the spatial patterns associated with each WCB stage from 2D atmospheric fields. The model uses for each WCB stage four different predictors (see Table 1 in Quinting and Grams (2022)) that can be calculated from temperature, geopotential height, specific humidity, horizontal wind components (u and v) at seven pressure levels (1000, 925, 850, 700, 500, 300, and 200 hPa). Additionally, a 30-day running mean trajectory-based climatology of WCB occurrence frequency is used as a fifth predictor. This set of inputs allows ELIAS to provide a computationally efficient and consistent Eulerian alternative to traditional Lagrangian trajectory calculations, offering a probabilistic footprint of WCB stages that is highly suitable for large-scale composite analysis.

The approach has been applied to ERA5 and compared with the WCB footprints derived from the Lagrangian ERA-Interim trajectories by Christ et al. (2025), who found the results to be consistent. ELIAS outputs a continuous probability field (0-100) for each WCB phase, that creates binary masks using pre-defined thresholds. In this study, we use a probability threshold consistent with Quinting and Grams (2022) to identify WCB footprints.”

- 6) Section 2.4: The deepening rate threshold applied here effectively limits the analysis to rapidly intensifying (“explosive”) cyclones. While focusing on these high-impact systems is a valid research choice, it introduces a substantial selection bias, as ordinary, moderately deepening cyclones also frequently feature ARs and WCBs. By discarding non-explosive systems, the subsequent composites likely overrepresent extreme moisture fluxes and precipitation rates. Therefore, this specific focus needs to be made transparent to the reader. Please explicitly state in the abstract/introduction/conclusion that this study focuses only on explosive cyclones. Additionally, please include a brief discussion addressing how this filtering choice influences the generalizability of the composite results compared to a standard, all-inclusive cyclone climatology.

Answer: We thank the reviewer for this important comment, as the description of the method was misleading. In particular, we would like to apologize for erroneously including the ‘explosive cyclones’ sentence, which is not correct. Pinto et al., (2009) set the minimum Laplacian thresholds (≥ 0.6 hPa/(degree latitude)² at least once during its lifecycle), the minimum deepening rate of 0.3 hPa/(degree latitude)² over 24h and the minimum travel distance of 1000km to remove non-synoptic relevant systems (e.g. semi-stationary heat lows). All these thresholds are comparatively low to warrant a full cyclone climatology also in marginal areas (e.g. the Mediterranean Basin; see also Pinto et al., 2005). Thus, the cyclone database is appropriate to compare with the AR database.

- 7) Section 2.5: In step (3), if no cyclone is found within 2000 km, the search radius is expanded to 4000 km. A 4000 km threshold spans almost an entire ocean basin and risks pairing an AR with a completely unrelated cyclone. Please provide a clear justification for using a 4000 km radius, and state what percentage of your total associated AR events fell into this 2000–4000 km window. If a significant portion of ARs are being linked to cyclones at these extreme distances, please discuss how these potentially unphysical pairings impact your analysis.

Answer: Zhang et al. 2019 and Guo et al. 2020 systematically quantified the distance between AR centroids and their associated ETC centers across the northern hemisphere, finding that the distance between the two systems varies from ~300 to >2000 km (in Zhang et al. (2019)) and from 500 to 1500km (in Guo et al. (2020)). Based on this, the former searched from an ETC around a 2500km box from the AR's centroid, and the latter at a 30° distance (~3300 kms). To note that while Guo et al. 2020 look at both northern and southern hemispheres, Zhang et al. 2019 only analyzed the AR-ETC distances on the North Pacific/U.S. West Coast. As such, we chose the primary radius of 2000 km. The secondary radius of 4000km is applied only when no ETC is found within 2000km. This two-step approach accounts for two specific scenarios: (i) decaying ARs where the associated ETC has weakened or moved rapidly poleward, and (ii) very large, occluded cyclones where the AR may be positioned further from the center than in the mature phase. This is applied to our analysis by adding the condition that the AR needs to be within 2000km from the ETC at least once during its lifecycle. A good example is the case study presented on section 3.2, where the AR is located closer to the ETC as it forms, but as it develops it starts to move eastward, farther from the ETC. The AR is still associated with the same ETC, but its distance increases. Of the 99.2% of ARs associated with ETCs, 95% of the time frames are found

within 2000km from the associated ETC. The remaining 5% of the time frames of ARs require the 4000 km radius, corresponding in general to the later stages of cyclone development when the warm sector and the AR are located very far from the cyclone core (the AR moves eastward away from the ETC as the system matures).

To account for this, in section 2.5 (‘Assignment of ARs to ETCs’), the second paragraph now yields:

“This procedure successfully associated approximately 99.2% of all ARs events with an ETC. The primary radius of 2000km follows the work of Zhang et al. (2019) and Guo et al. (2020), who systematically quantified the distance between AR centroids and their associated ETC centers across the northern hemisphere, finding that the distance between the two systems vary from ~300 to >2000 km (in Zhang et al. 2019) and from 500 to 1500 km (in Guo et al. 2020). Based on this, the former searched for an ETC around a 2500kmx2500km box from the AR’s centroid, and the latter at a 30° distance. As such, we chose the primary radius of 2000km. The secondary radius of 4000km is applied only when no ETC is found within 2000km. This two-step approach accounts for two specific scenarios: (i) decaying ARs where the associated ETC has weakened or moved rapidly poleward, and (ii) very large, occluded cyclones where the AR may be positioned further from the center than in the mature phase. This is applied to our analysis by adding the condition that the AR needs to be within 2000km from the ETC at least once during its lifecycle. The 2000km radius successfully associated approximately 95% of ARs with an ETC while the remaining 5% of ARs require the 4000 km radius (distribution shown in Figure A2).”

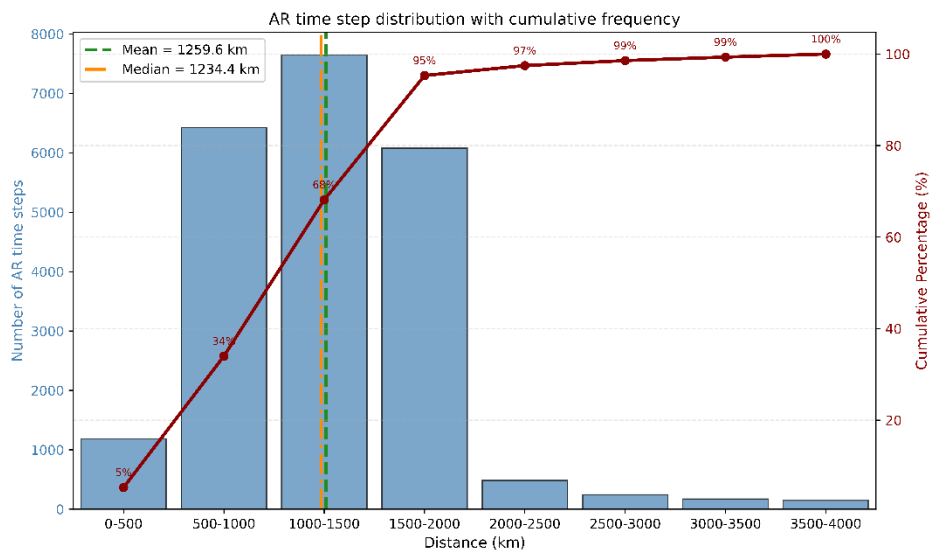


Figure 6 – Distribution of the distances between each AR object and the associated ETC (each 500 km). 95% of cases are within 2000km, leaving only 5% between 2000-4000 km. These correspond to 21332 and 1051 AR objects, respectively.

- 8) The number of events in each category (16’852 vs. 3’883) is currently not mentioned until Section 4.2. These sample sizes should be introduced much earlier in the manuscript, ideally right where the event classes are introduced in Section 2.7. Furthermore, these proportions differ significantly from those found by Sodemann et al. (2020), which you note in the introduction (23% of the AR overlap with WCBs, 40% occur in isolation). Please add a brief discussion somewhere in the manuscript addressing this discrepancy.

Answer: We agree with the reviewer that this discrepancy requires clarification. Accordingly, we added the following to section 2.7:

“This classification yielded 16,852 AR objects in the ascent-present category and 3,883 AR objects in the ascent-absent category over the 45-year period. This corresponds to approximately 81% of AR objects being coupled with WCB ascent, which is substantially higher than the ~23% overlap reported by Sodemann et al. (2020) for the Northern Hemisphere winter season.

Several methodological differences likely contribute to this discrepancy. First, our use of the IPART method (Xu et al. 2020), which identifies ARs based on spatial 'spikiness' rather than absolute IVT thresholds, tends to detect a broader range of AR intensities and shapes, including weaker systems that may be missed by magnitude-threshold methods.

Second, our analysis specifically requires the WCB ascent phase to overlap with the AR object, while Sodemann et al. considered overlap of any WCB trajectory phase (inflow, ascent, or outflow) with an AR.”

- 9) Section 3.1: In this section, the presentation of the new climatological results from Fig. 2 is blended with a broad literature review and general dynamical discussion. The immediate inclusion of citations to explain basic synoptic features (e.g., lines 275–286) dilutes the focus on the authors' actual findings and makes it difficult to distinguish new insights from well-established theory. Please restructure Section 3.1 to follow a more logical narrative. First, clearly and objectively describe the specific spatial patterns, peak frequencies, and overlapping fields revealed by Fig. 2. Once the results are clearly laid out, use a separate paragraph (or discussion section) to contextualize these findings with the existing literature. Additionally, when discussing the climatologies, please also include a discussion on existing literature that compares AR and WCB climatologies (in particular Sodemann et al. 2020), either here or earlier in the introduction.

Answer: We are grateful to the reviewer for suggesting a clear structure for this section. To account for these suggestions, we have restructured Section 3.1 as follows:

“Previous studies have examined AR and WCB climatologies separately (e.g., Sodemann et al. 2020; Madonna et al. 2014), but direct intercomparison of their spatial co-occurrence has been limited. Our Figure 2 provides the first combined climatological view of all three systems (ARs, WCB phases, and ETCs) using a consistent methodological framework.

The extended winter climatology of ARs, WCBs phases, and ETCs (Figure 2) reveals a coherent, co-located spatial pattern across the North Atlantic. All features exhibit maximum frequency along a southwest-northeast corridor extending from the Gulf Stream region towards Iceland and northwestern Europe. The peak of WCB inflow occurrence (Figure 2b) is located at approximately 37°N, 73°W, just off the eastern coast of North America. Eastward of this, the AR (Figure 2c), WCB ascent (Figure 2d), and ETC (Figure 2a) frequency maxima are located at approximately 40°N, 45°W; 45°N, 43°W; and 50°N, 45°W, respectively – exhibiting a progressive ~10° latitudinal northward offset. The frequency of ETCs associated with an AR (Figure 2e) peaks in the western North Atlantic, while the WCB outflow maximum (Figure 2f) is located southeast of Greenland.

While only about 30.5% of all ETCs have an associated AR, a remarkable 99.2% of detected ARs are linked to an ETC. This underscores that almost every AR in this region is an integral component of a larger synoptic-scale cyclonic system, acting as its primary moisture reservoir. The subset of ETCs that have an associated AR preferentially forms in the western North Atlantic (Figure 2e), directly over the Gulf Stream.

”

The discussion and literature review has been moved to the new discussion section:

“The spatial alignment of the three systems is dynamically consistent with the classical structure of mature ETCs, where the AR is positioned within the cyclone’s warm sector, typically to the south and southwest of the low-pressure center (Eiras-Barca et al. 2018; Zhang et al. 2019). The collocation of WCB inflow with the AR’s moisture plume confirms that the AR provides the moisture reservoir for the WCB, while the WCB ascent (located just ahead of the surface cold front) drives the conversion of this moisture into precipitation (Heitmann et al. 2024; Wernli and Gray 2024). The WCB outflow maximum southeast of Greenland is consistent with the anticyclonic branch of WCBs, which contributes to upper-tropospheric ridge building (Saffin et al. 2021; Vishnupriya et al. 2025). Our finding that 81% of AR objects in our sample are coupled with WCB ascent is higher than the ~23% reported by Sodemann et al. 2020, likely due to methodological differences as discussed in Section 2.7.”

- 10) Section 2.5: You mix up “peak intensity” and “Maximum Deepening Point” (MDP). MDP is the time of peak intensification (maximum pressure drop per time interval), which occurs before a cyclone reaches its peak intensity (minimum SLP). Please clarify how you are defining MDP and correct the terminology throughout the text to match the metric used.

Answer: We thank the reviewer for pointing out this important distinction. The MDP is defined as the time of maximum -hourly SLP deepening rate (i.e., the largest negative $\Delta\text{SLP}/6\text{h}$), which typically occurs before the cyclone reaches its minimum central pressure (peak intensity). In our analysis (sections 5.1 and 5.2), all temporal composites are centered on the MDP, not on peak intensity. We have revised the terminology throughout the manuscript to ensure consistency.

In section 2.4, we have added: “The MDP is defined as the time of maximum 6-hourly SLP decrease (i.e., peak intensification rate), which typically precedes the cyclone’s minimum central pressure by approximately 6-12 hours.”

- 11) Line 340: “WCB-influenced ARs occur closer to cyclones” – This can be expected, as WCBs are by definition associated with extratropical cyclones. I would briefly mention this.

Answer: We thank the reviewer for this comment. We have changed the sentence to:

“... ascent-present ARs occur closer to cyclones – a result that is expected, as WCBs are by definition associated with ETCs – which provides the stronger dynamical forcing necessary to sustain the intense WCB ascent.

”

- 12) The current titles for the two event classes, “WCB-influence” and “WCB-absent,” are somewhat awkward and imprecise. This nomenclature becomes particularly confusing in Figure 5b and on line 369 (“As per the WCB-absent cases (Figure 5b), the inflow is substantially reduced occurring at a maximum of 10%.”), as it is contradictory for a “WCB-absent” case to still exhibit non-zero WCB inflow frequencies. I would suggest to rename these two categories throughout the manuscript and figures to more intuitive, descriptive titles that explicitly clarify that you are sorting based on the presence or absence of WCB ascent collocation. And please revise the text (particularly line 369) to reflect this updated terminology, and briefly explain why inflow frequencies can still be non-zero in the non-collocated composite.

Answer: We thank the reviewer for this important suggestion. We agree that the terms ‘WCB-influenced’ and ‘WCB-absent’ are imprecise, particularly because WCB-absent cases can still exhibit WCB inflow or outflow (as seen in Figure 5b). To address this, we propose renaming the two categories throughout the manuscript to explicitly reflect the classification criterion, namely the presence or absence of the WCB ascent phase overlapping with the AR:

- ‘Ascent-present ARs’ (formerly WCB-influenced): AR objects where the WCB ascent phase overlaps with the AR
- ‘Ascent-absent ARs’ (formerly WCB-absent): AR objects where the WCB ascent phase does not overlap with the AR

This terminology is more precise and avoids the misleading implication that WCBs are entirely absent. It clarifies that the key dynamical distinction is the presence of the ascent phase specifically, while acknowledging that inflow or outflow may still occur in the vicinity—which explains the non-zero inflow frequencies we observe in Figure 5b. We have updated the entire manuscript.

For Figure 5b specifically, we revised lines 369-370 to clarify: “As per the ascent-absent cases (Figure 5b), the WCB inflow frequency is substantially reduced, occurring at a maximum of 10%. This indicates that while WCB inflow may be present near these ARs, the ascent phase—which is critical for precipitation generation—does not overlap with the AR itself.”

- 13) Fig. 5: I’m not sure I understand the units, is it the percentage of ARs that have a WCB (inflow/ascent/outflow mask) at the specific grid point?

Answer: Yes, the units of Figure 5 represent the percentage of ARs that have each WCB phase (per grid point). Caption of Figure 5 has been changed to: “Figure 5: Composite frequency of occurrence (%) for each WCB phase, aligned with the AR-centered composites in Figure 4. The frequency (%) at each grid point represents the percentage of AR objects in each category (ascent -influenced or ascent-absent) that have a WCB mask present at that specific grid point. (a, b) WCB inflow. (c, d) WCB ascent. (e, f) WCB outflow. Left column: AR events with WCB ascent influence. Right column: AR events without WCB ascent influence. Grey contours show the relative frequency of AR occurrence (drawn at 20% intervals, from 10% to 90%).”

- 14) Line 367: The authors state that “convergence occurs above 40%” when describing Fig. 5a. However, Fig. 5 shows the relative frequency of WCB occurrence, and not wind or moisture convergence. Please correct this terminology.

Answer: We apologize for the wrong terminology. The sentence has been changed to:

“Starting with the inflow phase, for the ascent-present cases (Figure 5a), we can observe that the WCB inflow frequency exceeds 40% on the northward side of the AR core...

”

- 15) Lines 373-374: “On Figure 5d, the WCB-absent ARs are generally located close to the lowest SLP values of Figure 4d ... “ – I don’t understand what you mean here. There are no SLP contours in Fig. 4d.

Answer: We apologize for the misunderstanding in the text. The correct phrase is “On Figure 5d, the ascent is located closer to the lowest SLP values of Figure 4b with a percentage of 5-10% of occurrence.” Changes have been made accordingly in the revised manuscript.

- 16) Section 4.2, lines 376–388: The second half of this paragraph shifts away from describing the figure into a broad discussion (e.g., orographic comparisons and forecasting implications). To maintain a clean narrative, please move these interpretive points into a dedicated discussion section, keeping Section 4.2 strictly focused on the objective description of the Fig. 5 composite fields.

Answer: We moved the interpretive content from line 376-388 of section 4.2 to the new discussion section, alongside other synthesizing remarks. Section 4.2 has been revised to focus strictly on the objective description of the composite fields shown in Figure 5.

The new discussion section is:

“The climatological interplay among ARs, WCBs, and ETCs in the North Atlantic constitutes a tightly coupled, process-driven system (Dacre et al., 2019; Dacre and Clark, 2025). Their three-phase structure is physically inseparable from ETC dynamics: the WCB inflow forces the wind convergence in the boundary layer; the AR is the signature of the organized transport of moisture, usually located equatorward of the low's center; and the WCB ascent forces the moisture upward, leading to precipitation formation and the release of latent heat reinforcing the cyclone's circulation (Sodemann et al., 2020). This trio forms a moisture-dynamics-thermodynamics feedback loop, where each component modulates the others' intensity and lifecycle.

The spatial alignment of the three systems is dynamically consistent with the classical structure of mature ETCs, where the AR is positioned within the cyclone's warm sector, typically to the south and southwest of the low-pressure center (Eiras-Barca et al. 2018; Zhang et al. 2019). The collocation of WCB inflow with the AR's moisture plume confirms that the AR provides the moisture reservoir for the WCB, while the WCB ascent (located just ahead of the surface cold front) drives the conversion of this moisture into precipitation (Heitmann et al. 2024; Wernli and Gray 2024). The WCB outflow maximum southeast of Greenland is consistent with the anticyclonic branch of WCBs, which contributes to upper-tropospheric ridge building (Saffin et al. 2021; Vishnupriya et al. 2025). Our finding that 81% of AR objects in our sample are coupled with WCB ascent is higher than the ~23% reported by Sodemann et al. 2020, likely due to methodological differences as discussed in Section 2.7.

The enhancement of IVT and spatial extent in ascent-present ARs is likely a direct consequence of the intensified low-level convergence associated with the WCB inflow phase, which draws in and concentrates water vapor over a wider area. The displacement of the heaviest precipitation northeast of the AR's IVT axis underscores that the core of maximum moisture flux and the region of most vigorous ascent are frequently misaligned. This weak signal in ascent-absent events likely arises from less efficient mechanisms like broad slantwise ascent or residual frontal lift, which lack the focused, enhanced vertical motion characteristics of a WCB. The composite results demonstrate that the WCB ascent and AR are not merely co-located, but the former plays a critical role in transforming the AR's moisture into a possible extreme precipitation event. This has direct forecasting implications: assuming precipitation is co-located with the IVT maximum would lead to significant forecast errors. The weak precipitation in ascent-absent events likely results from synoptic-scale slantwise ascent or residual frontal lift, which is less efficient at converting moisture to rainfall than the focused, convective-enhanced ascent within a WCB (Oertel et al., 2021).

The region where the highest precipitation matches the highest WCB ascent occurrence coincides with the typical location of the cyclone's warm front, where large-scale uplift and conditional symmetric instability can trigger deep convection (Wernli and Gray, 2024). This indicates that the WCB's organized ascent is the primary mechanism converting AR moisture into intense rainfall, a distinction crucial for operational forecasting, as it demonstrates that extreme precipitation is not merely a result of high moisture content but also strongly associated with the presence and location of strong ascent.

The phased evolution outlines a feedback loop: intense convergence (inflow) feeds both the AR and the cyclone. Diabatic release in the WCB ascent intensifies the cyclone (peaking at MDP) and generates intense precipitation within the AR. Finally, the cyclone's modification of the upper-level flow (outflow) begins to alter the large-scale environment, contributing to the system's decay. This tight temporal coupling, occurring within 12-hour windows, underscores that, for ascent-present ARs, the AR, WCB, and ETC should be considered an integrated, co-evolving system rather than independent features. This conclusion applied specifically to the subset of ARs associated with ETCs and overlapped with the WCB ascent phase. For ascent-absent events, such strong coupling is not evident, as the absence of WCB ascent appears to decouple precipitation generation from the cyclone's intensification. Latent heat release through condensation in the WCB ascent enhances cyclone deepening, creating a positive feedback loop where strong ascent leads to more latent heat, which deepens the low, which in turn strengthens the pressure gradient and the low-level inflow, feeding even more moisture into the system. This explains why the most extreme precipitation events are linked to the MDP of the associated ETC (McErlich et al., 2023). The dynamic interactions between these components are critical, as errors in forecasting the jet stream that steers an AR, or inaccuracies in estimating moisture availability, can lead to significant forecast errors (Lavers et al. 2020; Li et al. 2024).

The temporal evolution throughout the ETC development, with key transitions occurring within narrow ± 12 -hour windows, highlights the dynamical link, where the frequency of WCB ascent, the magnitude of IVT, and the spatial extent and intensity of precipitation all reach their maximum values at the exact time of the cyclone's most rapid deepening. This maximum ascent coinciding with the cyclone's strongest intensification is consistent with the climatological WCB lifecycle documented by Heitmann et al. (2024) for the North Atlantic, who similarly found that the most rapidly ascending WCBs are associated with the highest precipitation rates.

For forecasting, this means that accurately predicting the timing and location of the MDP is of utmost importance, as it serves as the point for the entire sequence of high-impact weather. This coupling explains the forecast errors documented by Lavers et al. (2020) and Li et al. (2024), where inaccuracies in the jet stream or initial moisture fields propagate through the system, leading to significant errors in the predicted location and intensity of the AR and its associated extreme precipitation. Moreover, while the magnitude of IVT is expected to increase with temperature due to the Clausius-Clapeyron relation (Payne et al., 2020), our results suggest that the dynamic component—specifically the presence and location of the WCB ascent—will ultimately determine future flood risk severity, requiring that climate models adequately resolve these process interactions. In addition, the sensitivity of WCB ascent characteristics to cloud microphysical parameterizations and inflow environmental conditions, as quantified by Oertel et al. (2025), further increases these forecast challenges. Their perturbed parameter ensemble demonstrates that uncertainties in the representation of microphysical processes locally modify vertical velocity along the WCB and determine precipitation efficiency, with distinct impacts on the spatial distribution and intensity of precipitation—precisely the features our composite analysis identifies as critical for extreme event outcomes.

The critical role of the WCB in converting moisture to extreme precipitation is underscored by previous work. For example, Catto et al. (2015) demonstrated that the role of the WCB in producing extreme precipitation events (EPEs), when matched with fronts, was found to be between 2 and 10 times more critical to EPE occurrence than when considering fronts alone. Similarly, Pfahl et al. (2014) showed that the percentage of extreme precipitation associated with a WCB is higher than 70%–80%. Building on this, our findings suggest that future work must use convection-permitting models to investigate the role of embedded convection within WCBs, a process that these studies identified as a key amplifier that our composite analysis could not fully resolve. Looking forward, this composite analysis should be expanded to other ocean basins to assess the universality of these dynamics. Addressing this gap is essential for understanding how the dynamic coupling identified here will shape the most severe midlatitude hydrological extremes in a warming climate.”

- 17) Lines 412–413: Concluding that ARs, WCBs, and ETCs are an “integrated, co-evolving system rather than independent features” is too generalized, as this section only analyzes a subset of pre-filtered ARs that include WCB ascent. Please rephrase this statement to clarify that this tight temporal coupling applies specifically to this coupled population, rather than generalizing to all AR events.

Answer: We agree with the reviewer. We have revised this statement to clearly indicate that this tight coupling applies specifically to the subset of ARs that are coupled with WCB ascent, rather than all AR events. The revised text reads:

“This tight temporal coupling, occurring within 12-hour windows, underscores that, for ascent-present ARs, the AR, WCB, and ETC should be considered an integrated, co-evolving system rather than independent features. This conclusion applies specifically to the subset of ARs associated with ETCs and overlapped with the WCB ascent phase.

For ascent-absent events, such strong coupling is not evident, as the absence of WCB ascent appears to decouple precipitation generation from the cyclone's intensification.”

- 18) Lines 422-425: The sentences defining IVT, contrasting it with precipitable water, and invoking the Clausius-Clapeyron relation are generic introductory concepts. To keep the focus strictly on the analysis of Fig. 7, I would suggest removing these sentences or moving them to the introduction.

Answer: We agree with the reviewer that the above-mentioned sentence should be removed from the end of this paragraph. We have change accordingly in the revised manuscript.

- 19) Lines 425-427: The number of cases should be introduced much earlier (at the beginning of Section 5, where the composite framework is first presented).

Answer: We thank the reviewer for the comment. We agree that the number of cases should be added at the beginning of section 5. As such, the new introductory paragraph is: “Based on the previous results, we now take a closer look at the variation of the 12-hourly composites at (and around) the MDP of each ETC that has an associated AR, from -24h to +24h from the MDP, each 12h to better understand how the AR-WCB coupling evolves dynamically with time. Only the AR cases that are influenced by the ascent phase are analyzed in this section. Note that the number of cases varies considerably from -24h to +24h of the MDP: the maximum occurs on the MDP, with 1343 cases, and the minimum at MDP +24h, with 266 cases.”

- 20) Section 5: The units “mm/AR” to describe precipitation amounts are non-standard. Please explain how “mm/AR” is calculated (e.g., is it an area-average over the AR mask, or an accumulated total?) to ensure clarity.

Answer: The units ‘mm/AR’ are calculated dividing the accumulated precipitation within all the ARs (within the number of cases presented on each composite title) by the number of cases. This gives us a mean value per AR case. To note that this is done for each grid-point. Since the same type of calculation is being done also on section 4, this clarification has been added to section 2.7 on the ‘Composite mean calculation’. New paragraph states: “the final composite fields for each event class were generated by computing the arithmetic mean of all aligned grids. This process yields a statistically representative model of the atmospheric state for each class, effectively filtering out the noise of individual case-specific features and highlighting the robust, systematic signals of the AR-WCB interaction. For example, the precipitation composite is calculated by accumulating the precipitation field of all ARs on each class (section 4) and on each 6-hours (section 5) and then dividing by the number of cases presented on each image title.”

- 21) Lines 446–447 state that “the highest decrease in SLP occurs between -6h and +6h of the maximum IVT.” However, the purple line ($\Delta\text{SLP}/6\text{h}$) is nearly horizontal from -24h to +6h, with only a very minor, barely visible minimum at $t = 0\text{h}$. Framing this almost-flat behaviour as a meaningful intensification window overinterprets a very weak signal. Please adjust the text to clarify that the deepening rate remains largely uniform during this period.

Answer: We agree with the reviewer that the change in the mean MDR (mean deepening rate) values is not a meaningful intensification, but rather a mean uniform value from -24h until +12h. We have clarified this in the revised manuscript, changing the phrase to: “As we observe in the mean distribution (purple line), the mean MDR values remain largely uniform from -24h to +12h of the IVT_{max} .”

- 22) Section 5.3 and Fig. 9: The text and axis labels refer to the purple line in Fig. 9 as the “Maximum Deepening Point (MDP).” Because the MDP is a single point in time, it cannot evolve continuously over a 48-hour window. It appears the authors are actually plotting the 6-hourly SLP change. Please correct this terminology throughout the section and figure caption.

Answer: We thank the reviewer for this important clarification. We apologize for the confusion – the purple line in Figure 9 does not represent the MDP itself (which is a point in time), but rather the maximum deepening rate (MDR) associated with the ETC that is paired with each AR. To clarify:

- For each AR, we identify its associated ETC and compute the maximum 6-hourly SLP decrease that occurs anywhere in the ETC's lifecycle. This is the ‘maximum deepening rate’ (hereafter MDR; sometimes referred to as the MDP magnitude).
- In Figure 9, we align these MDR values by the time of the AR's maximum IVT ($t=0$), and plot the distribution of these rates across all events.

We have revised the figure title and caption to read “Evolution of MDR (purple) and maximum IVT (green) around the time of maximum IVT within the AR” and update the axis label accordingly. In the text, we will use the term ‘maximum deepening rate (MDR)’ rather than ‘MDP’ when referring to these values, reserving ‘MDP’ for the temporal coordinate in Figures 6 and 7. This should eliminate any ambiguity.

Typos and wording:

Please note that the examples listed below are not exhaustive; please carefully revise the entire manuscript to ensure all remaining minor typos and grammatical errors are addressed.

- 23) Lines 58, 118: IVT (vertically integrated vapor transport), ECMWF (European Centre ...) The spelled-out word should come before the parentheses, with the abbreviation inside.

Answer: We have systematically check all abbreviations throughout the manuscript to ensure this convention is followed.

- 24) Lines 63, 121, caption Fig. 4, etc.: Please use the abbreviations “ARs”, “IVT”, “SLP” here and throughout the manuscript, as they have already been defined earlier (check also for other abbreviations).

Answer: We have reviewed the entire manuscript and replaced all instances of spelled-out terms with their established abbreviations after the first definition. This applies to the main text, figure captions, and section headings.

- 25) Terms such as “WCB inflow” and “WCB ascent” (lines 20, 98, 99, etc.) are used inconsistently with and without hyphens. Please standardize these throughout the text (preferably without hyphens, unless they are used as modifiers preceding a noun).

Answer: We have standardize all WCB phase terminology to use without hyphens throughout the manuscript.

- 26) Research question 2: The phrasing “time of maximum deepening point (MDP)” sounds slightly redundant. I suggest omitting “point (MDP)” and changing it to “time of maximum deepening”.

Answer: We have changed accordingly in the revised manuscript.

- 27) Line 173: “climatological” – Typo: “climatology”

Answer: We have adopted this wording.

- 28) Line 192: “degree.latitude” – “degree latitude”

Answer: We have adopted this wording.

- 29) Lines 240, 335: “composite” – typo: “composites”

Answer: We have adopted this wording.

- 30) Line 276: “inflow highest climatology” – replace by “highest inflow frequency”

Answer: We have adopted this wording.

- 31) Line 311: “coinciding” – change to “coincides”

Answer: We have adopted this wording.

- 32) Caption Fig. 4: Please specify what the purple circle stands for.

Answer: Purple circle represents the location of the low-pressure center from the SLP composite. This has been added to caption of Figure 4.

- 33) Lines 337, 338: do you mean “eastward” instead of “westward”?

Answer: We need to keep in mind that these are rotated composites. If we look at Figure 1, we see that, on the non-rotated field, the ETC is located northwestward of the AR centroid. Upon rotation, the ETC is located to the north of the centroid. The main conclusions here are: (1) the proximity of the ETC to the AR; (2) the presence of the AR where the

pressure gradient is at its highest (between the cyclone and the anticyclone). However, to not induce the reader in error, we have changed the phrase to:

"...a cyclone situated poleward of the AR centroid (north, in this rotated coordinate system) and an anticyclone to the south and east. In the original (non-rotated) geographical coordinates, this corresponds to the cyclone being located northwest of the AR centroid, consistent with the classical warm-sector positioning of ARs relative to ETCs."

34) Line 353: "rotate" – typo: "rotated"

Answer: We have adopted this wording.

35) Line 396: "How does ... varies ..." – change to "How do ... vary"

Answer: We have adopted this wording.

36) Lines 405–407: This sentence contains repetitive wording, using the phrase "high precipitation" twice. Please revise.

Answer: To account for the development of a separate discussion section, sections 4 and 5 have been re-organized. The information on this comment has been implemented in section 6.

37) Lines 490–492: Please rephrase for clarity. For example: "In AR-only cases, precipitation is substantially weaker (under 5 mm) and forms a diffuse northeastward extension toward the cyclone center. This weaker precipitation may be driven by synoptic-scale uplift, frontal processes, or residual ascent from prior WCB activity that was too weak to be detected by the ELIAS model."

Answer: We agree with the reviewer. Considering this and the other reviewer's comment, this sentence has been rephrased to: "In ascent-absent cases, precipitation is substantially weaker (with values lower than 5 mm) and forms a diffuse northeastward extent towards the cyclone center. This weak signal likely arises from less efficient mechanisms such as broad slantwise ascent or residual frontal uplift, which lack the focused, enhanced vertical motion characteristics of a WCB" To note that to account for the development of a separate discussion section, sections 4 and 5 have been re-organized. The information on this comment has been implemented in section 6.

38) Line 547: "has showed" – change to "has shown"

Answer: We have adopted this wording.