

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.

I thank the authors for addressing my previous comments, which have resulted in significant improvements to the clarity of the work. I am happy to recommend that this article be accepted for publication once the following minor comments are handled.

1. Lines 43-44: Identify IVT here first with "maximum vertically integrated vapor transport (IVT) defining an AR.." instead of later in line 59.

Answer: We have moved the definition to lines 43-44, which now read "... maximum vertically integrated vapor transport (IVT) defining an AR...", and removed the redundant definition previously at line 59.

2. Line 92: Make sure the year in Sodemann et al. 2020 is in parenthesis.

Answer: We have corrected this; the citation now reads "Sodemann et al. (2020)".

3. Line 121: Use only SLP here and define SLP earlier in lines 105-106 where it is first used.

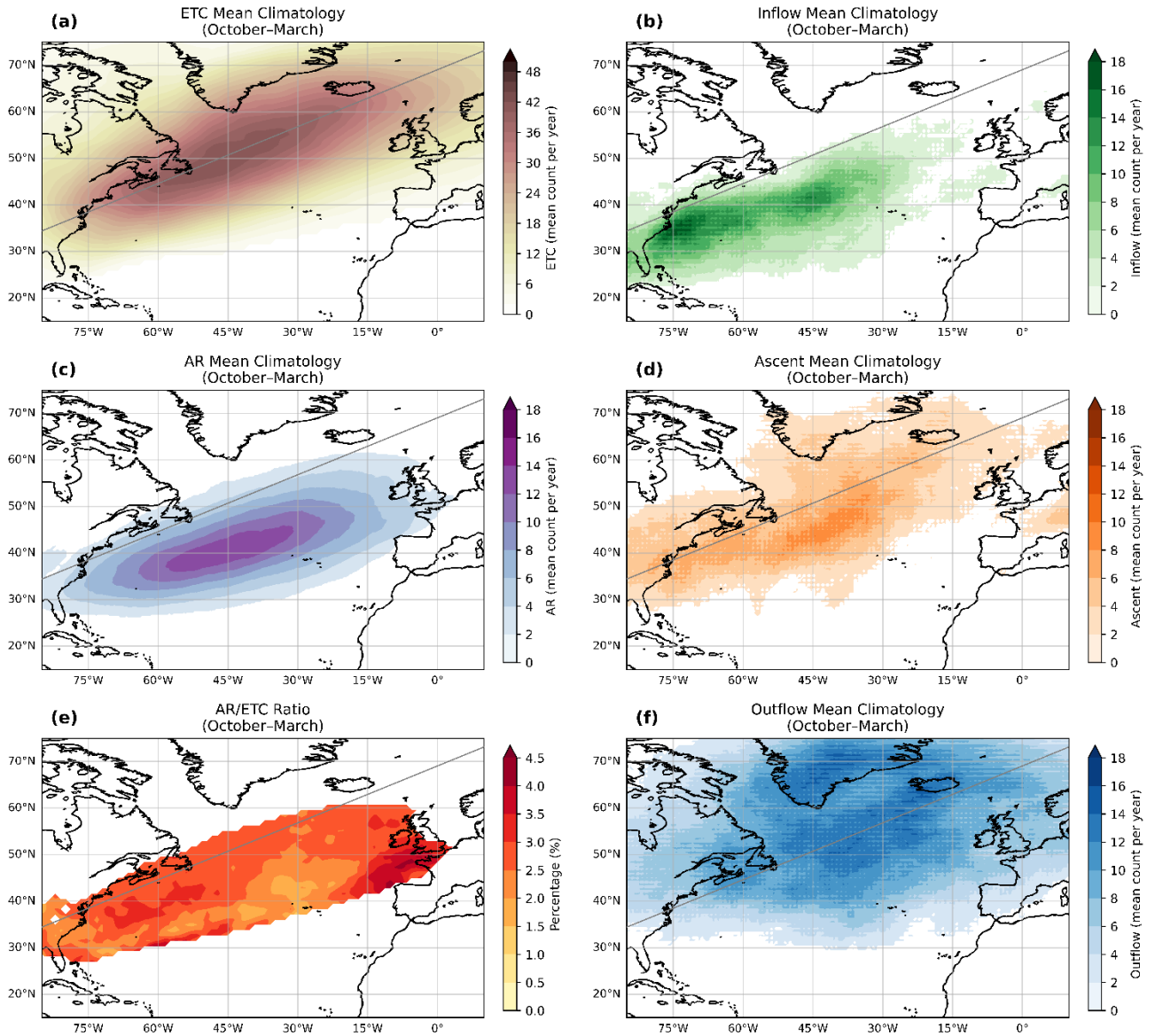
Answer: We agree with the reviewer. We have revised the text so that SLP is spelled out at first use in lines 105-106, with the abbreviation used consistently thereafter, including line 121.

4. Lines 240-241: Define the abbreviations first before using them, not vice versa.

Answer: We agree and have revised lines 240-241 to read "Maximum deepening point (MDP)" and "Maximum deepening rate (MDR)" instead. The terms are now defined at first use, before the abbreviation.

5. Figure 2: Grey line described in the caption is missing from all panels. Please either revise the figure to include the line or remove that sentence from the caption.

Answer: We are sorry for this mistake in the revised manuscript figure. We have added the missing grey line to all panels on the new Figure 2 (shown below), as described in the caption.



New Figure 2 – 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 shown in (a), for easier orientation.

6. Lines 366-368: This sentence either requires a reference to Figure 5a,b or should be omitted and saved for the next section.

Answer: We have added reference to Figure 5a and 5b. The sentence now states:

“The IVT rotated composites (Figure 4c and 4d) highlight a quantitative difference in moisture intensity. In WCB-coupled cases, the core IVT exceeds $1100 \text{ kg m}^{-1} \text{ s}^{-1}$, a threshold significantly higher than the sub- $1100 \text{ kg m}^{-1} \text{ s}^{-1}$ values observed in AR-only cases. This enhancement is not just a matter of intensity, as the spatial structure is also altered. The relative frequency contours of the AR itself are broader in the influenced cases, suggesting a larger spatial footprint. The data shows that the inflow phase occurs over 40% of the time north of the AR core in coupled cases (Figure 5a), compared to a mere 10% in AR-only cases (Figure 5b), providing a clear kinematic explanation for the observed differences in AR width and intensity.”

7. Line 431: Should be 7h, not 7i.

Answer: We apologize; the correct citation is Figure 7h.

8. Section 5.1: Discussion surrounding the results presented in Figure 6 for the inflow and outflow phases are a bit disjointed. For instance, it's hard to argue that the inflow phase has intensified from MDP-12 to MDP when their maximum values are the same. Additionally, at MDP+12 the ascent frequency is still at 25%, and 15% at MDP+24. Furthermore, for the outflow phase I'd word it that the outflow frequency increases and shifts downstream through the entire lifecycle, not just the MDP onward, and that peak intensity is at MDP+12, not MDP+24.

Answer: We thank the reviewer for this observation. We have corrected the timing described for each phase, including the outflow phase's peak at MDP+12h rather than MDP+24h. The new section states:

“The WCB inflow frequency (Figures 6a–6e) peaks during the pre-MDP period, with the highest frequencies observed at MDP–24h and MDP–12h (Figures 6a, 6b). At MDP–24h, the inflow frequencies exceed 20% within the AR's relative frequency contours (the 50%–70% interval), with the inflow region extending northeast from the AR centroid. By MDP–12h, the inflow is still above 20%, and the AR's spatial extent has expanded both zonally and meridionally. Afterwards, the inflow frequency begins to decrease slightly (to ~15% in Figure 6c), though it remains elevated at the MDP (Figure 6c). By MDP+12h (Figure 6d) and MDP+24h (Figure 6e), the inflow has weakened substantially, dropping to below 15%, consistent with the transition from the cyclone's intensification to its mature/decay phase.

In contrast to the inflow, the WCB ascent frequency (Figures 6f–6j) reaches its maximum at the MDP–12h and MDP (Figures 6g, 6h). At MDP–12h, the ascent frequency exceeds 20% within the AR's 50%–70% relative frequency contour, with the ascent region extending northeastward toward the cyclone center. At the MDP (Figure 6h), the ascent has intensified to over 25% and has expanded spatially, with the highest frequencies now located at the AR's leading edge, where the precipitation maximum is also observed (Figure 7h). This simultaneous peak in ascent and precipitation confirms that the WCB ascent is the primary mechanism driving the heavy precipitation within the AR. At MDP+12h (Figure 6i), the ascent frequency it's still presented above ~25%, while the spatial extent starts to contract, and, by MDP+24h (Figure 6j), the ascent weakens below 15% and is largely confined to a smaller region near the leading edge of the AR. The ascent region's northeastward displacement from MDP–12h to MDP+12h follows the typical trajectory of WCB parcels as they ascend along the cyclone's warm front, consistent with the climatological WCB lifecycle (Madonna et al., 2014; Heitmann et al., 2024).

The WCB outflow frequency (Figures 6k–6o) increases and shifts downstream throughout the entire ETC lifecycle. Although its frequency spans within 20–25% range to the northeast of the AR centroid before the MDP, its peak intensity occurs after the MDP, reaching a frequency of 30% at MDP+12h.”

9. Section 5.2: According to Figure 7 both IVT and precipitation actually peak at MDP-12 and maintain intensity through the MDP, please rephrase.

Answer: We agree and have rephrased this passage: both IVT and precipitation are now described as peaking at MDP-12h and remaining elevated through the MDP, rather than peaking at the MDP itself. The new section states:

“Throughout the intensification of an ETC, the associated AR exhibits a coherent structure, with IVT values consistently around $1000 \text{ kg m}^{-1} \text{ s}^{-1}$ over a 48-hour period centred on the cyclone's MDP (Figure 7a–7e). This persistence of high IVT, peaking at the MDP-12h and maintaining the high intensity through the MDP, suggests that the AR reaches a near-saturated

intensity state when the cyclone undergoes its most rapid intensification. The spatial extent of these ARs remains relatively consistent, spreading approximately 4200 km zonally (from -2100 km to +2100 km) and 1400 km meridionally (between -700 km and +700 km).

The evolution of precipitation within the AR-ETC system (Figure 7f-7j) provides a more detailed view of this coupling. At 24 hours prior to the MDP (Figure 7f), precipitation is relatively modest, approximately 6 mm/AR, and spatially confined near the AR axis. As the cyclone intensifies towards the MDP, precipitation increases to over 7 mm/AR and expands spatially, mirroring the characteristic shape of the WCB ascent region (Figure 6h). From the MDP-12h through the MDP (Figure 7h), the precipitation reaches its maximum values, exceeding 8 mm/AR, and the spatial pattern is distinctly asymmetric: the precipitation extends northeastward (on the MDP, Figure 7h) aligning closely with the WCB ascent footprint (Figure 6h), while the south-westward side of the AR remains relatively dry (values below 4 mm/AR). This asymmetry is characteristic of the warm-frontal structure, where the heaviest precipitation occurs ahead of the surface warm front, displaced poleward of the AR's moisture core.”

In addition to the points raised above, we would like to highlight the following change made during this revision. Upon further review of the manuscript, we revised the description of the ETC tracking method in Section 2.4. It now reads:

"The ETC tracks used in this study are based on the algorithm described by Pinto et al. (2005) based on Murray and Simmonds (1991). The algorithm is applied to the Northern Hemisphere (20 to 90 °N) and involves a multi-step approach, primarily focusing on the Laplacian of mean sea level pressure (∇^2 SLP). The process begins with the identification of local maxima in the laplacian field across the Northern Hemisphere, indicating regions of intense cyclonic circulation. Subsequently, the algorithm searches for corresponding minima in the raw SLP field that are in close vicinity to these laplacian maxima. If such a minimum is found, the cyclone is classified as a closed system, with its core located at the pressure minimum. If a pressure minimum cannot be found in the vicinity, the feature is defined as an "open system". If the laplacian value does not reach $0.1 \text{ hPa}/(\text{degree}.\text{latitude})^2$, the feature is eliminated. Cyclone information of different time steps is then combined into cyclone tracks (cf. Pinto et al., 2005). Only the cyclones that are considered as closed systems at least once during its lifetime are used in this study. To ensure that only synoptically significant cyclones are analysed, several filtering criteria are applied to the identified tracks (Pinto et al., 2005, 2009): (1) a minimum lifetime of 24 hours, eliminating short-lived systems that typically do not contribute significantly to large-scale weather patterns; (2) at least once in its lifetime, the laplacian must exceed a minimum threshold of $0.6 \text{ hPa}/(\text{degree}.\text{latitude})^2$; (3) a minimum deepening rate of $0.3 \text{ hPa}/(\text{degree}.\text{latitude})^2$ over 24h; and (4) a minimum travel distance of 1000km. This ensures that non-synoptically relevant systems (e.g. semi-stationary heat lows, features that remain open systems during their lifetime) that are unlikely to be associated with either ARs or WCBs are removed. Topographic influences are also accounted for by discarding cyclones located over high orography, specifically above 1500 meters. This cyclone tracking approach compares well with other methods, particularly for strong long-lived systems during the central part of their lifetime (Neu et al., 2013).

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.

The authors have dedicated significant effort to this revision and have thoroughly addressed my concerns. The updates have substantially enhanced the overall clarity and quality of the manuscript. I have only a few remaining minor points and wording suggestions outlined below prior to publication.

Specific comments:

1. While I appreciate the authors' effort to rename the AR categories, the new category names "ascent-present ARs" and "ascent-absent ARs" still feel somewhat imprecise and awkward. Omitting "WCB" removes important context, and phrases like "fields of ascent-present events against those of ascent-absent" (line 292) read unnaturally. Re-evaluating this in light of overall readability, I recommend returning closer to your original nomenclature using "WCB-coupled ARs" versus "Isolated ARs" (or "AR-only cases"). To avoid reader confusion regarding non-zero WCB inflow/outflow in the "AR-only" composite, please include a brief statement in line 388 reminding readers that the classification is strictly based on the presence of co-located WCB ascent, rather than the total absence of surrounding WCB features. Finally, if you adopt new category names, please verify all occurrences across the manuscript to ensure the updated phrasing integrates seamlessly into the text.

Answer: We thank the reviewer for this comment. We agree that omitting the term 'WCB' removes important context, and therefore we decided to adopt once again the overall classification names of 'WCB-coupled ARs' and 'AR-only events' in the new version of the manuscript, including figures headers when needed). In addition, to not induce the reader in confusion when stating the presence of inflow and outflow on the AR-only cases, we will remind that the classification is strictly based on the presence (or not) of co-located WCB ascent. This is all clarified in the revised manuscript that includes the following sentence:

"Starting with the inflow phase, for the WCB-coupled cases (Figure 5a), we can observe that convergence occurs above 40% to the northward side of the AR core, between the 70 and 90% of the AR relative frequency isolines, and spreads westward following a similar spatial extension as the AR relative frequency. As per the AR-only cases (Figure 5b), the inflow is substantially reduced occurring at a maximum of 10%. It should be noted that (1) the AR-only cases classification is strictly based on the presence (or not) of co-located WCB ascent and, as such, the inflow and outflow phases can still occur; and (2) WCB-coupled cases correspond to 16852 AR objects and the AR-only to 3883 AR objects (an AR object corresponds to one time step case detection)."

2. While 95% of AR–ETC pairings fall within the primary 2000 km radius, I suggest briefly mentioning that the extended 4000 km search window may occasionally capture coincidental pairings with unrelated cyclones.

Answer: We agree with the reviewer and have added a sentence to section 2.6 stating: "We note that the extended 4000 km search radius may occasionally capture coincidental pairings with unrelated cyclones."

3. In your answer to question 8 from R2, you write that, in Section 2.7, you added "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." However, the second part of this sentence is missing in the revised manuscript.

Answer: We apologize for the missing sentence. Upon final review, before uploading the latest version of the study, we moved the sentence to the Discussion section. Unfortunately, we did not update the answer to the reviewer. This comparison with the work of Sodemann et al. (2020) is stated in section 6-Discussion and states:

“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). Several methodological differences likely contribute to this discrepancy. First, our use of the IPART method, 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. (2020) considered overlap of the WCB trajectory (as an object, instead of the three phases separated) with an AR.”

Typos and wording:

1. Line 16: “overlapped with” – change to “overlapping with”

Answer: We have made this change.

2. Lines 175-176: Change sentence to “Trajectories are only considered if, first, they ascend by at least 600 hPa in 48 h and, second, they are matched with an ETC.”

Answer: We have revised the sentence as suggested.

3. Line 512: Sodemann et al. – year is missing

Answer: We have added the year; the citation now reads “Sodemann et al. (2020)”.

4. In lines 517–524, the explanation regarding 'slantwise ascent or residual frontal lift' in ascent-absent events is repeated in almost identical words two sentences apart. Please consolidate these into a single sentence (retaining the Oertel et al. 2021 citation) to eliminate the redundancy.

Answer: We agree and have consolidated the two repeated explanations of the AR-only signal into a single sentence, retaining the Oertel et al. (2021) citation:

“This weak signal in AR-only 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 (Oertel et al., 2021). 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.”

5. Line 564: “Similarly, Pfahl et al. (2014) showed that the percentage of extreme precipitation associated with a WCB is higher than 70%–80%.” – difficult to understand, I suggest to change the sentence to “Similarly, Pfahl et al. (2014) showed that 70-80% of extreme precipitation in the extratropics is associated with a WCB.”

Answer: We have revised the sentence as suggested.

In addition to the points raised above, we would like to highlight the following change made during this revision. Upon further review of the manuscript, we revised the description of the ETC tracking method in Section 2.4. It now reads:

"The ETC tracks used in this study are based on the algorithm described by Pinto et al. (2005) based on Murray and Simmonds (1991). The algorithm is applied to the Northern Hemisphere (20 to 90 °N) and involves a multi-step approach, primarily focusing on the Laplacian of mean sea level pressure (∇^2 SLP). The process begins with the identification of local maxima in the laplacian field across the Northern Hemisphere, indicating regions of intense cyclonic circulation. Subsequently, the algorithm searches for corresponding minima in the raw SLP field that are in close vicinity to these laplacian maxima. If such a minimum is found, the cyclone is classified as a closed system, with its core located at the pressure minimum. If a pressure minimum cannot be found in the vicinity, the feature is defined as an "open system". If the laplacian value does not reach $0.1 \text{ hPa}/(\text{degree.latitude})^2$, the feature is eliminated. Cyclone information of different time steps is then combined into cyclone tracks (cf. Pinto et al., 2005). Only the cyclones that are considered as closed systems at least once during its lifetime are used in this study. To ensure that only synoptically significant cyclones are analysed, several filtering criteria are applied to the identified tracks (Pinto et al., 2005, 2009): (1) a minimum lifetime of 24 hours, eliminating short-lived systems that typically do not contribute significantly to large-scale weather patterns; (2) at least once in its lifetime, the laplacian must exceed a minimum threshold of $0.6 \text{ hPa}/(\text{degree latitude})^2$; (3) a minimum deepening rate of $0.3 \text{ hPa}/(\text{degree latitude})^2$ over 24h; and (4) a minimum travel distance of 1000km. This ensures that non-synoptically relevant systems (e.g. semi-stationary heat lows, features that remain open systems during their lifetime) that are unlikely to be associated with either ARs or WCBs are removed. Topographic influences are also accounted for by discarding cyclones located over high orography, specifically above 1500 meters. This cyclone tracking approach compares well with other methods, particularly for strong long-lived systems during the central part of their lifetime (Neu et al., 2013).