Answer to Reviewer 1

The aim of this study is to investigate the processes leading to projected future changes in mid-and upper-level PV anomalies through a Lagrangian analysis of cyclone airstreams. The authors analyse changes in several variables along Lagrangian back trajectories initiated at different locations within the cyclone composites. They conclude that the majority of the PV tendencies occur within the last 24 hours before they reach their initiation point. They attribute the low-level PV tendencies to ascent in the WCB but cannot simply attribute upper-level PV tendencies to a cyclone airstream. The figures are well presented, and the structure of the paper is easy to follow. I enjoyed reading the paper.
The authors have attempted to link their previous Eulerian analysis to this Lagrangian analysis which is interesting, particularly the cyclone-centred composites of Lagrangian tendencies. My main concern about the analysis, is that the cyclone airstreams discussed are not explicitly identified. A cartoon of the airstreams is shown in figure 1, but the same airstreams are not identified with sufficient accuracy in the analysis of the data (see general comments below). As the aim of the paper is to link PV anomalies to cyclone airstreams, I think this needs to be addressed before the paper is suitable for publication.

We appreciate and thank you for reading our manuscript and giving such constructive feedback. Below, we address your concerns point by point. The figure and line numbers refer to the original manuscript. The reviewer comments are in black and our responses are highlighted in blue.

Major comments

Figures 3 and 7 show cyclone-centred composites of Lagrangian tendencies and how they are projected to change in the future. These figures are nicely presented but I struggled to identify the cyclone airstreams in these figures.

Thanks for this detailed and constructive comment. Our main goal is to link the Eulerian composite changes identified in part I to Lagrangian changes in air mass trajectories and properties, for which, in our opinion, the Lagrangian composites are a useful tool. Nevertheless, as you have emphasized, linking these composites to the classical air stream perspective is complicated, e.g., due to the fact that the composites show averages over many trajectories arriving at the same location relative to the cyclone center (meaning that, for instance, if some trajectories move westward and others eastward, the mean effect will be a small change) and that the tendencies from different locations in the composite do generally not refer to the same air masses (we thus cannot easily trace specific air streams through the composites). We have decided to not try to make the link with the air streams more explicit, e.g., through identifying the air streams with quantitative criteria (such as the 600 hPa ascent criterion for WCBs, see Madonna et al., 2014), because this would have added another angle to an already methodologically complex study, and because future changes in WCBs identified in this way have already been studied in the same model simulations (Joos et al., 2023; Binder et al., 2023). Nevertheless, we think that a qualitative comparison of our Lagrangian composite results with the air stream concept is useful. This also follows previous studies (e.g., Catto et al., 2010; Dacre et al., 2012) that discussed cyclone air streams based on Eulerian composites. We will improve the corresponding discussion in the revised manuscript, in particular, by adding a new figure showing the Lagrangian lon/lat changes relative to the cyclones displacement, as you have suggested below (see Fig. R1 in this document).

On line 226 the authors link the northward, ascending flow in the cyclone's warm sector to the WCB. The region of maximum ascent is located close to the cyclone centre, but the region of maximum poleward displacement is located further north-east, what region specifically is linked to the WCB and how does this relate to the WCB illustrated in figure 1? Furthermore, the WCB is typically comprised of two branches, one ascending and turning anticyclonically at upper levels and another ascending and turning cyclonically at mid-levels. While there is evidence of the anticyclonic branch in figure 7b, there is no evidence of the cyclonically turning branch. Line 304- 305 states that the reduced eastward transport in the WCB outflow region corresponds to an intensification of the WCB outflow that wraps around the cyclone centre, but the flow is still westward and hence not cyclonic. Is this because the cyclonic branch is located at a lower pressure level? If so, can cyclone-centred composites of Lagrangian tendencies at this lower pressure-level be shown. The cyclonic branch is also missing from the figure 1 illustration. Line 347 states that ascent in the eastern part of figure 8c is associated with the cyclonic WCB branch wrapping around the cyclone centre. Please can the authors present evidence of this cyclonic branch. Finally, line 450 refers to the cyclonic and anticyclonic branches of the WCB. More evidence is needed to support this conclusion.

The absence of spatial alignment of the regions of maximum ascent and maximum poleward transport in the composites at 700 hPa is related to the fact that different locations in the composites air associated with different air masses. The air parcels near the cyclone center appear to have ascended most before arriving at 700 hPa, while the air parcels in the warm sector east of the center have experienced a stronger northward displacement, but slightly less ascent. Nevertheless, these air parcels in the warm sector are embedded in a vertically extended region with strong ascent (maximum 24h ascent at upper levels, see Fig. 9a), which is most likely a signature of the warm conveyor belt. This is what we mean in line 226, and we will try to make this more explicit in the revised manuscript.
To identify the cyclonic WCB branch, the new Fig. R1 is particularly useful, as anticipated by the reviewer. While there is still no mean westward flow relative to the cyclone center in the composite at 250 hPa, a region of westward motion is evident at 500 hPa, indicating that the outflow of the cyclonic branch is located at somewhat lower altitudes, as suggested by the reviewer. This is consistent with the region of maximum ascent in the cross section in Fig. 8a and will be discussed in more detail in the revised manuscript. The cyclonic branch will also be added to the schematic illustration in Fig. 1.

Line 227 links the descending southward flow to the DI. Like the WCB, the DI is typically comprised of 2 branches, one turning cyclonically at low-levels and another turning anticyclonically near the surface (as stated on line 74). The anticyclonic branch is missing from the figure 1 illustration. While there is evidence of the cyclonic branch in figure 3b, there is no evidence of the anticyclonically turning branch. Also, in line 413 the authors state that some DI trajectories arrive to the west of the cyclone moving southeastward at low levels and others to the east of the cyclone moving northeastward close to the cyclone centre. Is this motion shown in figure 10a? I do not see any eastward motion in this figure, which shows pressure tendencies, or in figure 3b which shows longitudinal tendencies.

There is no indication of an anticyclonic DI branch in our composites. This could be associated with case-to-case variability in the occurrence and location of this air stream, which leads to cancellation effects in the composites. For instance, previous studies have shown that the anticyclonic branch can be located relatively far away from the sea level pressure minimum (Catto et al., 2010; Fluck and Raveh-Rubin, 2023). With regard to the second part of the comment, we are not sure what the reviewer refers to, as there is prevalent eastward motion 5° south of the cyclone center in Fig. 3b (and also the new Fig. R1 throughout the troposphere).
Note also that some structural differences can be found between our results and Dacre et al., 2012, with regard to the location of the DI region. In our case, the descending trajectories are located south of the cyclone center instead of upstream. These differences can be attributed to the fact that we do not rotate the fields in the storm direction.
For consistency with previous studies, we will add an anticyclonic DI branch in Fig. 1 and add a short comment to the manuscript that this branch, however, cannot be identified in our results.

The authors state on line 71 that the CCB can produce PV anomalies in the lower and middle troposphere, but analysis of this airstream is entirely missing from the paper. They also state that the CCB consists of 2 branches (line 67) but only the cyclonic branch is shown in figure 1 for some reason. Is this because no identification of the CCB airstream is possible from the data using the current latitude and longitude tendencies (figures 3a and b).

As for the DI, we will modify Fig. 1 to show both branches of the CCB. However, the CCB is not evident in our Lagrangian composites and thus not further discussed in the manuscript. We will add a corresponding note to the introduction.

To address the points above, the authors should also show figures of the cyclone-relative tendencies of the trajectories. I.e., subtract the cyclone motion 24hr latitudinal and longitudinal tendency from the trajectory tendencies. This will illustrate the cyclone-relative trajectory tendencies and will likely highlight the missing WCB and DI branches and the CCB.

Following your suggestion, we will add a figure with the cyclone-relative tendencies (Fig. R1) to the manuscript. At low levels, in present-day (contours), the Figure provides more comprehensive evidence of the trajectories traveling to the south upstream and north downstream of the cyclone. Westward trajectories are more evident to the northwest of the cyclone center, while eastward trajectories are more evident to the southeast of the cyclone center. Thus, we confirmed the WCB location, ascending to the southeast of the cyclone center and wrapping up northwest of the cyclone center at middle levels.
Note that the future changes in cyclone-relative tendencies are very similar to the absolute tendencies shown in Figs. 3 and 7 in the manuscript.

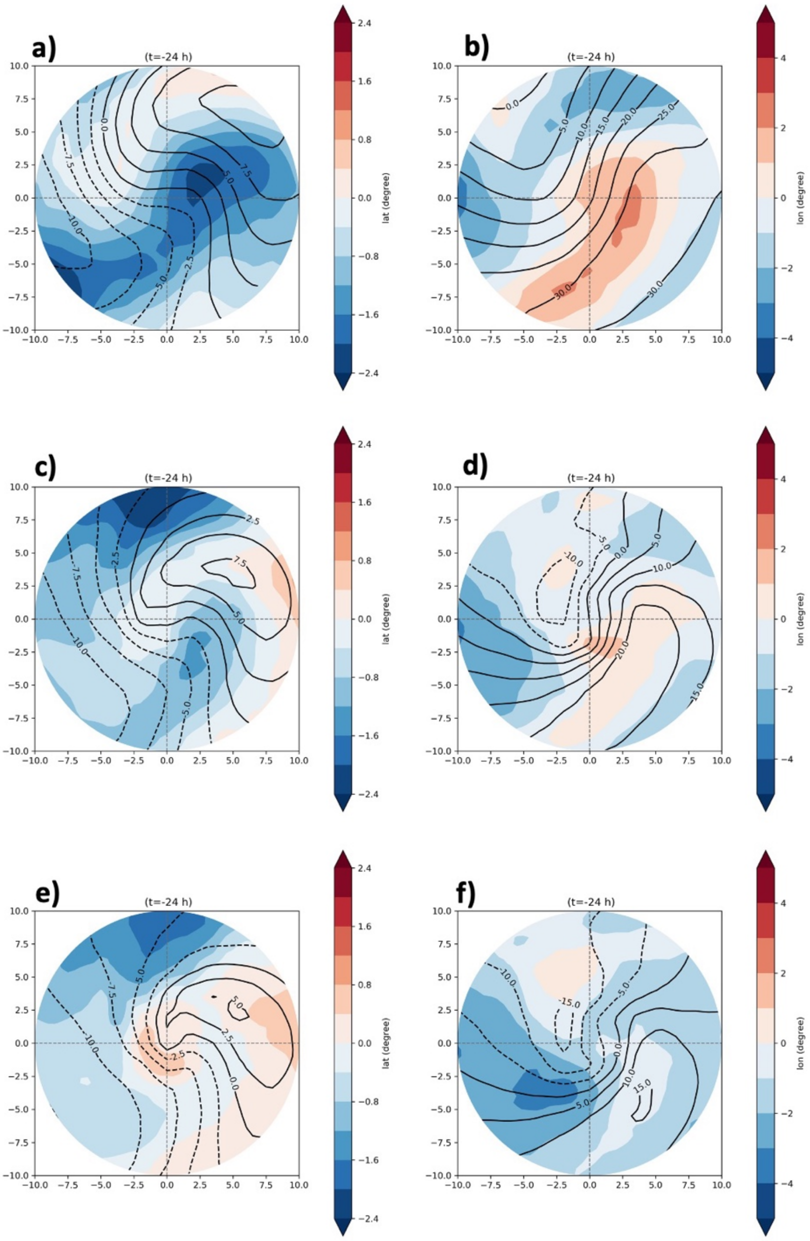

Figure R1. Composites of Lagrangian tendencies along backward trajectories initialized at (a, b) 250, (c, d) 500 and (e, f) 700 hPa in the last 24 hours before arrival in the cyclone area of (a, c, e) latitude and (b, d, f) longitude relative to the movement of the cyclone (i.e., with the 24 h longitude and latitude changes of the cyclone center subtracted). Contours show present-day Lagrangian tendencies, and the color shading indicates the response to future climate change (difference in the Lagrangian tendencies between future and present-day climate).

Minor comments

1. Line 103. Should 'proving' be 'providing'?

We will modify 'proving' to: providing

2. Line 148. If averaging over the entire cyclone area leads to cancellation between ascending and descending airstreams, why is this analysis presented? They also have a very large spread (line 176) meaning that interpretation of the averages is difficult.

We think that this analysis, although providing a relatively rough picture due to the averaging, is still useful for introducing the framework and giving first indications, for instance, of the relevant time scales. Despite the spread, we have shown differences between the lower and upper levels trajectories and estimated the time of most significant changes in several parameters to be 24 h before the initialization time. Furthermore, the basic effect of the warming climate becomes clear, that is an increase in potential temperature and specific humidity.

3. Figure 2. Is the shading around the present-day average the grey or red shading?

The gray shading corresponds to the present-day average. We will modify in the caption as follows:
Temporal evolution of (a,b) pressure, (c,d) latitude, (e,f) longitude, (g,h) specific humidity, (i,j) potential temperature and (k,l) PV averaged over all trajectories initialized within a 10° radius around the cyclone center of all selected cyclones and at (left column) 700 hPa and (right column) 250 hPa. The average for present-day climate is shown as blue, dashed line, the average over the future time slice as red line. The 5. and 95. percentiles are shown in gray shading for present-day and red shading for future climate.

4. Line 187: In the 24 h before what?

We will change this sentence to:
Trajectories reaching the cyclones at 700 hPa experience a clear PV increase in the 24 h before the maximum intensity.

5. Line 220. I suggest that the trajectories from the north have smaller absolute meridional displacement because the cyclone's themselves are typically travelling northwards enhancing to the airstream trajectory component in that direction (see major comments).

Yes, this is correct, as shown in the new Fig. R1. We will add a comment to the revised manuscript.

6. Line 223. I suggest that the relatively small region of westward displacement would be more significant if cyclone-relative longitudinal tendencies were plotted. This would give a better indication of cyclonic wrap-up of the air around the cyclone centre.

Yes, see again Fig. R1. We will add a comment to the revised manuscript.

7. Figure 5 and others. I think the description of blue and red lines should also be in the figure caption.

We will modify the caption for figures 4-6 by adding: The average for present-day climate is shown as blue, dashed line, the average over the future time slice as red line.

8. Line 281.'Righ' should be 'right'.

We will modify 'Righ' to: right

9. Line 282. 'th' should be 'the'.

We will modify 'th' to: the

References

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