Final author comments on wcb-2021-37

We would like to thank both reviewers for their very helpful comments and suggestions, which further improved our manuscript. Below we provide our responses (in blue) to all comments by the reviewers (in italics). Please refer to the line-by-line track changes in the attached PDF.

Reviewer #1

Specific comments

My main correction to this paper is that the precision with which some of the results are described could be improved. This correction mostly relates to the varying descriptions of quantifications based on figures 4 and 5.

Thank you for your extremely thorough corrections. We homogenized the way that the results are presented throughout the paper according to your suggestions. Please refer to our line-by-line comments below.

It would be good to also explicitly say that this is how the percentages and PV anomalies are calculated in the text (in the paragraph at L256).

We improved the explanation of how the percentages are calculated on L255.

L20 / L21 / L24 / L295 / L297 / L331 / L361 / L364 / L369 / L436 / L437 / L443 / L448 / L450 / L457 / L463 / L466 / L472 / L474

Thank you for your many excellent suggestions, we adopted them.

L14: You need to briefly introduce what "both seasons" means.

Thank you. We added the time span of both seasons in brackets.

L16: Given the average PV anomaly for long-wave radiative heating is very similar for cold and warm seasons, would it be more accurate to say that the strength/relevance of PV anomalies generated by turbulent mixing is increased in the warm season?

While the average PV anomaly generated by long-wave radiative heating (see below) remains roughly identical, significantly fewer cyclones are found with long-wave radiative heating as the primary process reducing PV. On the other hand, the number of cyclones with PV modification primarily by one of the two types of turbulent mixing remains approximately equal. Therefore we

decided to highlight the change in the number of systems primarily affected by long-wave radiative heating, which likely arises because of the warmer surface temperatures in summer.

L17: You are only talking about turbulent mixing of momentum but saying "turbulent mixing" implies also turbulent mixing of temperature

Thank you, we change the sentence to "turbulent mixing of momentum" to be more specific.

L19: This sentence implies that these are the only processes that contribute to the negative PV anomaly. In this case, 19% of warm fronts are dominated by "other" processes and even if that wasn't the case, it does not rule out processes contributing to the negative anomaly but not being the dominant process in any individual cyclone.

Thank you. We added "primarily" to clarify this.

L263: This first sentence has the correct structure and other sentences should generally follow this pattern. I would add that the area-weighted mean is the average over all Cyclones.

We added "averaged over all cyclones in this category." This hopefully additionally helps to clarify the meaning of the PVU values in the following figures (see combined answer below).

L264: You don't account for whether convection is more important in the remaining 18% of cyclones where neither condensation nor convection are the dominant process.

Absolutely, we followed your suggestion.

L217: "increasing PV on average by 0.86 PVU in every second cyclone" implies that this average of 0.86 PVU is taken from the subset of warm fronts where condensation is the dominant PV producing process rather than being an average over all warm Fronts.
L265: These two sentences are slightly contradictory. You first say that the cyclones have intense long-wave cooling which would imply these 14% of cold-season cold fronts have a much larger PV anomaly due to long-wave cooling than the cold-season cold fronts where other processes dominate. However, you then suggest that the other processes only generate weak PV anomalies in these cold fronts where long-wave cooling is the dominant process. You would need to calculate the mean PV anomaly for each process in each subset of cold fronts to say which is true here. I don't think this is necessary since you show the composite environments for the different subsets of cyclones in the following section.
L272: Again, this sentence implies that the PV anomaly is calculated from a subset of warm fronts rather than being an average over all warm fronts
L273: The PV increase of 0.94 PVU is the average over all cyclone but this sentence implies

it is the average over the subset
L274: This implies that ~33% of cyclones have a negative PV anomaly due to long-wave heating equal to -0.45PVU but I'm assuming the -0.45PVU is an average over all Cyclones
L277: The "x PVU in y%" again implies that the PV anomaly is calculated from a subset of cyclones
L282: This sentence implies that the average PV anomalies are calculated from the subset of cyclones
L283: Implies that the average of -1.47PVU is over the 14% subset
L284/287: Implies that the averages are taken from the subsets of cyclones
L291: Implies that the averages are taken from the subsets of cyclones

Please apologize for the confusion, these sentences are correct. We indeed calculate the mean PV anomaly of each process for individual subsets of cyclones, i.e. the area-weighted mean APV values shown in Figures 4, 5, and 6 represent the PV values produced by that specific process averaged only over the cyclones where that process is the most important. This way, the mean PV anomaly for a specific process does not consider cyclones with a different primary process as this would bias the intensity towards too low values. We hope to have clarified this with some minor modifications to the legend of Figure 4 and the text.

L274: This implies that the negative tendencies are only present in 60% of cyclones but I assume it is the dominant process in 60% of cyclone but likely present if most, if not all, cyclones

Yes absolutely. We corrected the meaning of the sentence.

L281: Does "boundary-layer processes" mean the combination of turbulent mixing terms and long-wave heating?

Yes exactly.

L289: Implies that these other processes are only present in ~20% of the cyclones but I assume you mean a different process dominates in 20% of cyclones

This is accurate, we updated the sentence by adding "primarily" to reflect the actual meaning.

L296: More important -> more often dominant

We corrected the meaning of the sentence.

L17: The average PV anomaly for turbulent mixing of momentum is larger than the average PV anomaly for condensation in both seasons. So isn't the PV anomaly at the warm front predominantly generated by turbulent mixing of momentum even though condensation is the predominant process in the majority of cyclones during

the cold season?
L18: While convection is rarely the dominant process generating PV at the warm front in an individual cyclone, it has a large average contribution across all cyclones. The average PV anomaly for convection is larger than the average PV anomaly for condensation even though it is the dominant process in so few cyclones.
L301: Primarily generated -> most often dominated by. The average anomaly due to turbulent temperature tendencies is larger so I would say that turbulent temperature tendencies are the primary generator of negative PV here
L449: Is this correct? Although it is dominant in a smaller percentage of cyclones, turbulent temperature tendencies provide the largest average PV anomaly
L470: Condensation has the smallest average PV anomaly across all cyclones of the three processes shown but is most frequently the dominant process in an individual cyclone.

As mentioned above, the value of the average PV anomaly only represents that specific subset of cyclones. Hence, if a process is the most important one in more cyclones but contributes on average less than another process this implies that the latter process, although leading to large PV anomalies when it is the most important one, is generally only active and relevant in few cyclones.

L302: Being produced -> most often dominated

We changed the sentence to “with negative PV primarily produced”

L314: Is the main driver -> is often the main driver

Changed to “condensation is frequently the primary driver of increased PV”

L382: is primarily generated by condensation, convection, and turbulent momentum tendencies -> is most often primarily generated by condensation, convection, or turbulent momentum tendencies

In this case we think that “primarily generated by” fits well, since only a single cyclone was found with a different primary process. However, we exchange “and” with “or” in “is primarily generated by condensation, convection, **or** turbulent momentum tendencies”.

L396: Wind speeds -> maximum vertical velocities

The wind field in the last column of Figure 9 in fact shows horizontal velocities, specifically the instantaneous 10 meter wind gust. We updated the legend label and figure title to clarify this.

L444: Does “this process” refer to generation of PV by long-wave radiative cooling?

Yes, we replaced “this process” with “long-wave radiative cooling” to be more specific.

L455: The slight change in sentence structure here now implies that condensation only increases PV in 49% of cyclones.

Thank you for noticing, we updated this sentence to be in line with our previous phrasing.

Other corrections

L260: What fraction of trajectories end up being excluded by these criteria?

With our approach, we remove 49% and 66% of trajectories associated with positive and negative PV anomalies, respectively. On average, 56% (54%) of all trajectories are excluded from further analysis during the cold (warm) season. This rather strict constraint ensures that our approach is valid for the trajectories used in the assessment and we obtain robust results. We added this information to the manuscript on L260.

When using a more relaxed selection criterion which does not constrain the magnitude of the residual, we find that the resulting statistics on the primary processes modifying PV remain largely unchanged (compare Fig. C1 with Fig. 4). For this sensitivity assessment, we only required the diagnosed PV change to have the same sign as the actual change in PV along the trajectory. Thereby, only 15% (25%) of trajectories associated with positive (negative) PV anomalies are removed.

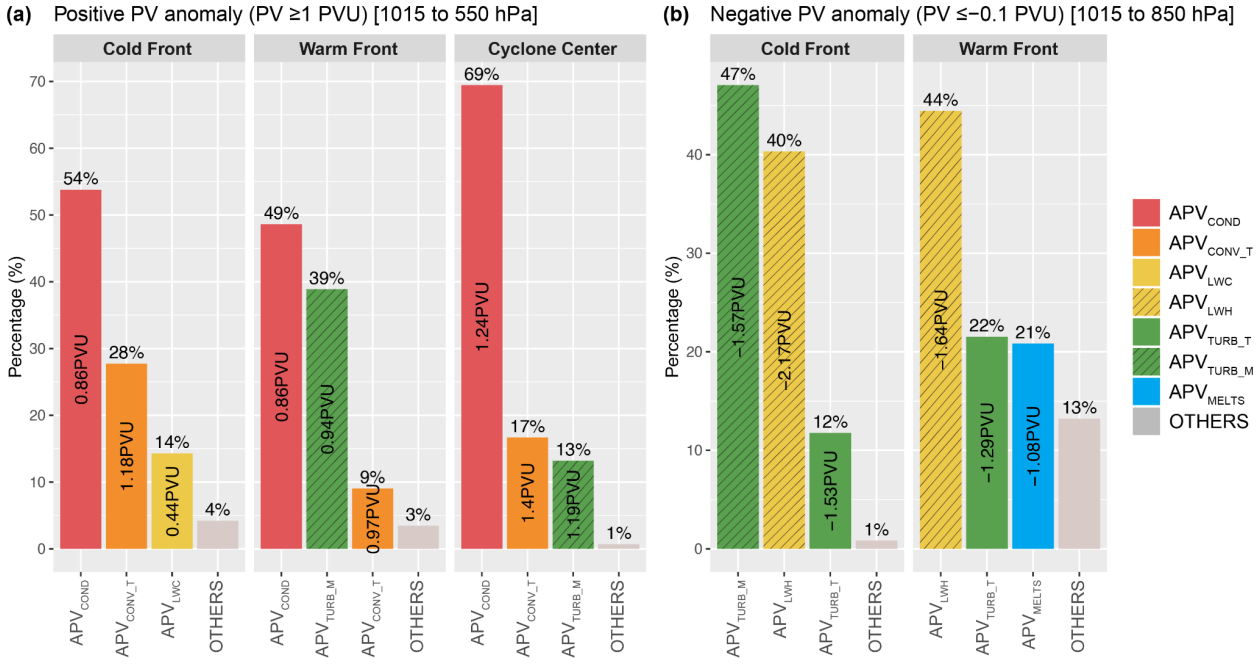

Figure C1. Identical to Fig. 4, but using all trajectories where the sign of the diagnosed PV change agrees with the sign of the observed PV change, i.e. regardless of the magnitude of the residual.

In figures 7, 8, and 9 it is difficult to read the grey contours where they overlap dark colours

We selected a slightly brighter color for the grey contours to improve legibility in areas with dark background colors, thank you.

In figures 7, 8, and 9 it is good that you have a diverging colourscale centered at zero for anomalies (T2M - SST and ETSS) but for the other fields it is misleading. Especially when you have centered T2M and SST at zero in figure 9 but not figure 7 or 8. It would be good if you could use a different colourscale in this figure for fields which are not anomalies.

Thank you for this suggestion. We modified the color scale for fields that are not anomalies.

L335: What happens in your composites of SST when the cyclone is over land?
L401: "surface and sea surface temperatures" implies the composites are simply "surface temperature". If this is true can you change the figure captions accordingly

Thank you for these remarks. We noticed that our SST field was set to 0°C over land, leading to biased SST composites when cyclones over land were included. To remedy this issue we replaced SST with surface skin temperature (SKT), which is mostly identical to SST over the ocean and represents the surface temperature over land. We re-calculated all composites and now include the temperature difference between the 2 meter temperature and surface skin temperature instead. This change did not significantly affect the composites nor the interpretation of the results.

Technical corrections

We corrected various spelling mistakes, thank you for pointing them out to us.

Reviewer #2

General points

The abstract is too long with too many details included. It needs to be condensed.

Thank you, we shortened the abstract.

The conclusion section is indeed a summary of the results with repeated sentences without further explanation and dynamical interpretation. This section is also too long and should be shortened to focus on the main findings of the present study with necessary interpretation.

Unfortunately, investigating the exact dynamical response of each individual PV anomaly generated by the different diabatic processes is beyond the scope of this paper. Moreover, we find that most of the information presented in the conclusions are relevant. Still, we attempted to slightly shorten the conclusions in addition to the changes requested by Reviewer #1.

As described in the pioneer work of Hoskins et al. (1985) and in some other researches, rapid cyclogenesis can be explained by an interaction between low and upper level PV anomalies in which mid-level PV anomalies also act to intensify this process. Consequently, it is not right to assess the relevance of individual diabatic processes involved in the dynamics of rapidly intensifying extratropical cyclones in the absence of complex feedbacks acting in the real atmosphere. Therefore a precise explanation of this important issue in a suitable section would be beneficial.

We completely agree that the best way to understand rapid cyclogenesis is by considering the interaction between anomalies of lower and upper-level PV, and of surface potential temperature. We mention this important concept in our manuscript in the first sentence of the 3rd paragraph of the introduction. The goal of the present study, however, was merely to assess the generation processes of low-level PV anomalies without any further consideration of the active or passive role of individual PV anomalies for the intensification of the cyclone or downstream development. Assessing the exact relevance of the investigated PV anomalies for the evolution of the atmospheric flow is beyond the scope of the present paper and was therefore not included.

It can be useful to calculate some statistical significance level for the differences between the results in the two seasons and/or various categories.

We argue that computing levels of statistical significance is not feasible given the still comparatively low number of cyclones and therefore not very robust statistics that could be obtained, e.g. for the fractions provided in Figures 4 and 5. Moreover, the large differences, e.g. between the different categories for the generation of the positive PV anomaly along the cold front (53%, 29%, 14%) imply that no added benefit from statistical significance testing would be

gained. On the other hand, it is correct that one can currently not distinguish if, for instance, melting of snow or turbulent temperature tendencies are more prevalent for the generation of negative PV anomalies along the warm front in the cold season.

What is the reason of choosing a specific year (December 2017 until November 2018) as the study period in this paper?

The first simulations for this study were performed in December 2018. The study period was simply defined by the then most recent possible period for starting hindcast simulations covering an entire year.

What is the reason for discussing only a single cyclone in subsection 3.2?

The cyclone shown in Fig. 2 provides an exemplarily depiction of the different PV anomalies that can occur along the frontal features of extratropical cyclones. We think that such a case study is very useful for the reader to get an impression of how the anomalies look like for a given cyclone. Note that the discussion of PV anomaly statistics (intensity, size, and height) in subsection 3.2 pertains to the entire available dataset consisting of 144 cyclones during the cold and 144 cyclones during the warm season.

I pointed to some questions raised in different parts of the paper; please pay attention to these points.

Unfortunately, no additional material was supplied. However, we have thoroughly reviewed the manuscript and corrected, to the best of our knowledge, any spelling and formatting mistakes.