Answer to Reviewer 3

This manuscript uses back trajectories to better understand how the potential vorticity structure and thus the dynamics of extra-tropical cyclones will change in a warmer climate. The main conclusions are that in a warmer and moister climate, enhanced ascent and latent heating in warm conveyor belts leads to a stronger low-level PV anomaly. In contrast, upper-level PV anomalies response in a much more complicated manner which the authors show is due to changes in advection and hypotheses that changes to radiative cooling near the tropopause are also important. Overall, the manuscript is well written, easy to follow, and the conclusions are well supported by the presented evidence. I have two concerns with this manuscript which I describe below, and numerous rather minor comments also listed below.

Thank you for reading our manuscript and for your constructive comments, which will help us to better communicate our results. In the following, we reply to your points. The figure and line numbers correspond to the original manuscript. The reviewer comments are in black and our responses are highlighted in blue.

Major comments:

1. Almost all of the results are presented as averages over all extreme cyclones. Cyclones are highly variable in their structure and dynamics. The impact of this variability is not taken into consideration in this study. Specifically:

a) Line 137-138 "we evaluate various parameters averaged over all trajectories initialised in the cyclone area, in a radius of 10 degrees around the SLP minimum" – this is a huge area and includes air masses with very different properties e.g., the cold sector, the warm convector belt. This huge variability is seen in Figure 2. Does this make scientific sense to average so many different trajectories together? However, in the other extreme, the authors then proceed to show trajectories from just one grid point (Figures 4, 5 and 6) which potentially are not representative. I strongly encourage the authors to re-consider their approach as I expect that much clearer and informative results may be obtained if trajectories only from certain areas of the cyclone were averaged together. Another recommendation, if the approach in Figures 4 – 6 is kept, is to include a measure of uncertainty on these figures, similar to what is done in Figure 2.

It is correct that cyclones can be highly variable and event-to-event differences may play an important role, e.g., for assessing the impacts of an individual storm. Nevertheless, in part I of this study we have shown that, also when averaging over many extreme cyclones, there is a *systematic* change in some of their properties in a simulated future climate, which warrants further investigation. We thus consider it as a valid and important approach to focus on the explanation of such mean changes also in this second part of the study.

We agree that the trajectory plots shown in Fig. 2 and those in Figs. 4-6 represent two "extremes" of the spectrum of possible analyses, but we would argue that the Lagrangian composites shown in Figs. 3 and 7 (and the cross sections in Figs. 8-10) fill the gap between these extremes. We think that Fig. 2, 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. The Lagrangian composites then directly provide what the reviewer is asking for: they show the spatial variability of the Lagrangian changes in the cyclone region, without the need to predefine specific regions for spatial averaging. The trajectories in Figs. 4-6 serve as illustrative examples of these changes, and their spatial representativeness can again be determined from the Lagrangian composites in Fig. 3.
We will include the 5-95[th] percentiles as shading also in the figures showing the trajectories from individual locations. Also for those, there is substantial variability due to the fact that more than 300 cyclones are considered. This variability would further increase if we'd average over a region.

b) How do the magnitudes of the changes detected relate to the amount of variability in the control simulation? Or stated another way, are these results statistically significant? Figures 3 and 7 should include information showing where the changes are significant.

We will include stippling in the Lagrangian composite plots indicating where more than 80% of the ensemble members agree on the sign of the projected change.

2. Section 3. Some additional details of the simulations should be added here as it is not reasonable to expect a reader to read part 1. Even some basic information such as what time periods the simulations cover (this is in the abstract but could be repeated here), what resolution the simulations are performed at (the coarse resolution is noted as a limitation of this study in the conclusions, but a reader is not told what it is) would be appreciated. I also suggest that a few more details are given about the strongest 1% of cyclones – how many cyclones are there in absolute numbers in both the historical and future climate simulations? Do they all occur in a certain part of the north Atlantic or do they cover a huge geographic area? What metric is used to measure intensity?

We will add more information in the data and methods sections as follows (new information is highlighted in yellow):

2 Data

We have selected ten members from the CESM-LE-ETH ensemble, which were restarted from CESM-LE simulations (Kay et al., 2015) proving 6 hourly output fields on model levels that are required for our trajectory calculations (see section 3). The periods 1990-2000 (present-day climate) and 2091-2100 (future climate, under the RCP8.5 scenario) are analyzed. This fully coupled model has a horizontal resolution close to 1 degree (~0.94° in latitude and 1.25° in longitude). More details are provided in Sect. 2 of part 1.

3 Methods

We study Lagrangian airstreams in the 1% strongest cyclones in the 10-member CESM-LE dataset for the extended winter season (from October to March). This cyclone dataset is described in detail in part 1. Based on the SLP contouring method (Wernli and Schwierz, 2006), we identify and track storms over the North Atlantic region (longitude: -100° to 40° and latitude: 30° to 90°). The cyclone intensity and, thus, the extreme cyclone selection (1%

strongest cyclones) are obtained by computing the relative vorticity at 850 hPa at the cyclone center. The number of extreme cyclones is 358 in the present-day and 308 in the future climate. In present-day climate, the cyclones typically travel towards the northeast, with the peak cyclone frequency south of Greenland. At the end of the century, the storm track is projected to shift eastward, implying a higher impact in the north of the United Kingdom and the west coast of Scandinavia.

Minor comments:

1. Line 52. Units Wm-2 is missing the negative sign.

We will modify Wm^2 to: Wm^{-2}

2. Line 58. "This PV ascent and descent"... This is rather strange, suggest revising it.

We will change this sentence to:
These PV changes are due to ...

3. Line 69 – 70. This second branch of the cold conveyor belt is never mentioned again in the results section / the analysis so does it really exist on average or is this a rare feature?

The cold conveyor belt is usually difficult to distinguish, especially at the cyclone mature stage, because it can merge with the WCB cyclonic branch. It is not evident in our Lagrangian composites and thus not further discussed in the manuscript. We will add a corresponding note to the introduction.

4. Line 163, these values of specific humidity seem to be very small, however, it may be due to the large area that they are averaged over. Is this a valid hypothesis?

The 95th percentile is slightly above 4 g/kg, so spatial variability does play some role. Other reasons are the decrease of specific humidity with height (recall that we are looking at the 700 hPa level) and the fact that the cyclones typically reach their maximum intensity relatively far north.

5. Lines 170 – 200. This section discusses many of the processes we would expect in the warm conveyor belt, yet the results being discussed include all of the cyclone areas. This section should at least reminder a reader that the average trajectories also include those arriving in the cold sector.

This could be associated with the changes in the WCB trajectories being stronger than the other airstreams, having a more predominant signal. We will add the following sentence at line 183 to clarify that we are considering the trajectories arriving in the whole cyclone area:
Recall that we have averaged the trajectories arriving in the cold and warm sectors.

6. Line 210 – could the location of these points be added to a composite map?

Yes, we will add markers to the composite plots.

7. Figures 3 and 7. The units on the colour bar on panel (c) are missing. It might also be a good idea to state in the caption here how many cyclones these composites were created from.

The units are provided in our PDF version of the preprint.

We will modify the captions and include the number of storms:

Figure 3. Composites of Lagrangian tendencies along backward trajectories initialized at 700 hPa in the last 24 hours before arrival in the cyclone area of (a) latitude, (b) longitude, (c) pressure, (d) potential temperature and (e) PV. 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). A total of 358 and 308 storms are considered in the present-day and future climate, respectively.

8. Line 282 – typo "th" → the

We will modify th to: the

9. Figure 7e. There is a small area of negative PV tendency in the control simulation. I don't think this is discussed in the text. Is this related to negative PV tendencies about the localised heating maximum in the warm conveyor belt?

Yes, this is likely related to the PV destruction that the trajectories experience when reaching the upper levels. We will add a note on the negative values around line 300, where we discuss the corresponding process.

10. Line 310 – 327. There are many references to figures / results in part 1. This makes it quite difficult for a reader to follow without going to find the figures in part 1. Could this be revised so a readers' understanding does not require part 1?

Since the main goal here is to explain the PV anomalies identified in part I, we think that it is necessary and useful to refer to the respective figures from part 1.

11. Line 405-406. Can the references to the figures be added here? e.g., figure 2 for the Lagrangian composite at 700hPa.

Yes, we will modify the sentence to:
The Lagrangian tendency composite at 700 hPa (Fig.3), the north-south vertical cross-section through the cyclone center (Fig. 8c,d) and the time series in Fig. 4 (left column) show a descending airstream south of the center with characteristics of a dry intrusion (Raveh- Rubin, 2017). To study the spatial pattern of this DI in more detail, we analyze the west-east vertical cross-section (4) 4o south of the cyclone center, as shown in Fig. 10.

12. Line 424. Could add here what intense really means e.g. top 1% which is X numbers of

cyclones.

Yes, we will add more details, see below:

In this study, we have used a Lagrangian perspective based on air parcel trajectory calculations to investigate projected future changes of air streams in intense North Atlantic extratropical winter cyclones as well as their role for PV anomaly changes. The 1% strongest cyclones are considered, amounting to 358 cyclones in the present-day and 308 cyclones in the future climate.