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Interactive comment on "Mid-level convection in a warm conveyor belt accelerates the jet stream" *by* Nicolas Blanchard et al.

Nicolas Blanchard et al.

florian.pantillon@aero.obs-mip.fr

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We thank the Referee for his/her time and his/her constructive comments. We have complied with most of the proposed changes. In the following, the comments made by the Referee appear in black, while our replies are in blue.

The paper contains a comprehensive case study analysis of convection embedded in a warm conveyor belt and its impact on the upper-level flow. The study combines unique observations taken during the North Atlantic Waveguide and Downstream Impact Experiment and convection-permitting simulations of the case study. The observations are compared to a reference simulation and an experiment in which heat exchanges due to cloud processes are turned off (called NODIA). Generally, the reference sim-

ulation agrees with the observations whereas key features are missing in the NODIA experiment, highlighting their diabatic origin. In particular, elongated bands of absolute negative PV are missing in the NODIA simulation. Their impact on the upper-level flow is hence missing in NODIA. These findings support the theory developed in Harvey et al. (2020) and are consistent with those seen in a different cyclone's WCB (Oertel et al. 2020). The case included in this study has been the subject of several recent articles (Maddison et al. 2020, Blanchard et al. 2020), including a recent publications by the authors, and this contribution adds useful new insights to complement the recent research, particularly with the novel observations within the WCB. I thus recommend the article be published subject to minor revisions. I have a couple of broad comments that should be considered before publication and specific and technical comments listed below.

Broad comments:

1) Clarification of online trajectories versus the WCB.

A more careful consideration of how the trajectories shown in the article relate to the WCB ascent would be beneficial. The authors select trajectories in the simulation that ascend 150 hPa in 12 hours (based on the 600 hPa in 48 hour criteria for WCBs used in many other studies). As this is a short time period the trajectories shown don't necessarily correspond to the WCB, as the authors note (section 2.3). As the simulations are run for 36 hours I wonder if there are some trajectories that stay in the domain for longer than 12 hours and could be used to show whether the 12 hour ascents do correspond to part of the WCB or not. Alternatively, successive 12 hour trajectories could be compared in an attempt to "piece together" the WCB flow. This cyclone has been shown to have a WCB (e.g. Maddison et al. 2019) so I would suggest emphasising this (in section 2.3) and terming the ascents "WCB proxy" or something similar. Some properties of the trajectories could then be better explained and would allow for a better placement of the results in the current knowledge. For example, from Figure 7 it appears that the anticyclonic ascents are from the later stages of a WCB ascent (the start at 4km), and the cyclonic ascents from the early part. Also, the characteristic increase and decrease in PV along WCB ascents (e.g. Madonna et al. 2014) is not found here. These should be further explained.

We clarify that the selected ascents "may not all belong to actual WCB trajectories" and refer to Blanchard et al. (2020) for a discussion of the selection criteria. Technically, the scalar tracers used to compute the trajectories are advected during the full 36-h model integration time thus the length of trajectories could be extended. However, the reason for choosing a 12-h window is the domain size, as explained in Section 2.3: "This relatively short time window is chosen to ensure that all relevant trajectories remain in the simulation domain during the 12 h period." (Note that the domain is relatively small compared to earlier WCB studies but still contains 800x800x70 grid points due to the high horizontal resolution.) This is illustrated in Figure 6, where most ascents reaching the red box at the time of observations (11 UTC) are located close to the southern domain boundary at the time of initialization (00 UTC). In particular, the anticyclonic ascents—which "feed" the jet stream core and constitute the WCB outflow—head northward with high velocity at upper levels and their trajectories could be extended by a few hours at most. In contrast, the cyclonic ascents appear to remain longer in the domain but do not contribute to the WCB outflow and jet acceleration thus are not extensively studied here. We clarify that the focus is on the former, especially in Section 5. Finally, the evolution of PV along cyclonic and anticyclonic ascents is further discussed in the text but does not contradict earlier studies (see also response to specific comments).

2) Verification of the simulations against the observations.

Throughout the paper the authors compare the reference and NODIA simulations with each other and with the observations. It would be helpful if the authors included some verifications (e.g. RMSE) to clarify and emphasise the comparisons as it is sometimes difficult to see by eye. I would suggest quantifying the simulations' skill in replicating the observed fields in Figures 1, 2 and 3 (comparing points where observations exist). And also comparing the two simulations with each other in Figures 5 and 8. For example, the authors state that the ridge extends further west in the reference simulation so quantifying this somehow (most westward longitude reached for example) would be helpful as it is a bit confusing because of the complicated structure of the ridges. Also the jet stream maxima should be highlighted in the two simulations and discussed more as the title states that the jet stream is accelerated by the convection in the WCB.

Several metrics have been added to better compare the simulations and assess them against the observations: the Heidke Skill Score is now computed when comparing Meso-NH BTs with BTs measured by MSG (in addition to already comparing the simulated MSLP with the analysis); quantitative statements are included in the comparison of wind speed between RASTA observations and Meso-NH simulations; finally, the bias and the RMSE are given for the comparison between wind speed, potential temperature and relative humidity measured by the dropsondes and simulated by REF and NODIA.

3) Labelling features of interest.

Several features are referred to in the text that are not always easily recognisable among the highly detailed plots. The authors give latitude or longitude points to guide the reader but this can be quite cumbersome. Adding labels (maybe shapes or simply letters) to the plots for some of the features would help with the comprehension of the

results. The features mentioned in the text that I would suggest labelling include: the high PV tongue, the tropopause fold, the jet cores, the WCB outflow, the bent back front, the low-level jet and the cloud head. Too many labels can of course obscure features and make the plots more complicated but adding one or two labels to some of the figures when latitude/longitude values are needed in the text would be helpful.
The suggested features of interest are now labeled in maps and vertical cross-sections in Figs. 1, 2, and 3, while references to geographical coordinates have been omitted when unnecessary.

Specific comments:

L22: PV gradients form a waveguide on zonal flows too (without upper-level ridges or troughs), this should be mentioned here. "Zonal flows" are now mentioned.

L86-88: more information on the other parameterisation schemes in the model should be given here. In particular, would other schemes contain heat exchanges within clouds that would still be active in NODIA? We added "Note that the other parameterizations (radiation, turbulence, shallow convection) also exchange heat in the atmosphere, but in a negligible way compared to cloudy processes."

L128: is this a second MSLP centre (were there two?) or just an eastward movement of the cyclone? Evidence should be provided if it is a second MSLP centre development. The evidence of a second MSLP center is given in Fig. 1b in Blanchard et al. (2020). To clarify, the sentence is now "The abrupt shift is due to the creation of a second MSLP center to the east (see MSLP at 16:00 UTC in Fig. 1b in Blanchard et al. (2020)), which therefore has a diabatic origin."

L206: The fact that the observations are well simulated in REF allows for the attribution of features and their development to diabatic processes. This should be emphasised here. Added

L220: What are the ascents over Greenland associated with? We did not investigate the ascents in detail but their presence in NODIA clearly shows their origin is not diabatic. As explained in the following paragraph "They are likely produced by the combined effect of the warm front dynamics and orographic forcing caused by the Greenland Plateau."

L225-226: I find it surprising that there are almost no ascents in the WCB outflow in NODIA. Is it that the WCB is absent or that the trajectories don't meet the ascent threshold used? It could also be a timing issue in that WCB trajectories may be delayed in NODIA. Would figure 5 look different if a slightly later 12 hour window was chosen? Further explanation should be included here. Indeed they may be trajectories that rise slowly but do not meet the used threshold and thus do not qualify as "ascents" in NODIA. We are actually not surprised as latent heat release associated with cloud diabatic processess—which are switched off in NODIA—are essential to WCB ascents. We added "This absence of trajectories rising by at least 150 hPa in 12 h is consistent with lower cloud tops in NODIA than in REF."

L243: It would be beneficial here if a brief explanation of why/how the anticyclonic trajectories would be expected to impact the upper level flow, via PV modification for example. We added "via injection of low-PV air"

L250-265: can the results be explained here using extratropical cyclone development theory? Does the cyclonic branch of the WCB typically occur later than the anticyclonic? The PV modification along the trajectories is different here than that found in Madonna et al. (2014). There is no increase in PV (as trajectories ascend through heating) and subsequent decrease (as trajectories leave heating). May this have occurred earlier in the ascent? This should be explained here too. The 12-h time window we use for trajectory analysis is too short to compare when the cyclonic and anticyclonic branches of the WCB occur in the Stalactite cyclone, which is beyond the scope of the study. However, for this window, Figure 7 shows that PV actually increases at low levels (cyclonic ascents) and decreases at higher levels (anticyclonic ascents), as expected below and above the diabatic heating maximum along slantwise ascents. This was clarified in the text.

L285: Another feature that is clear in Figure 8 is the PV field is smoother in NODIA. This should be mentioned and explained. We do not fully agree: the PV field shows small-scale features in both NODIA and REF (see the cloud head area for example). The main difference between the two simulations lies in the negative PV bands.

L289: mention that the negative PV bands at 06:00 push the ridge cyclonically to the west as well. We added that they "push the ridge to the west" (and omit "cyclonically" to avoid confusion).

L320-326: Why is there no PV dipole for the strong updraft above 6km altitude? Has the PV signature been dissipated by this time? Please explain this here. This may be due to the weaker vertical wind shear but is rather speculative and not discussed in the paper. However, we note that the absence of a PV dipole happens for the strong updraft above 6 km altitude "that does not meet the criteria for rapid segments", which validates the identification of rapid segments based on pressure difference.

L353: Do heat exchanges still occur in other parameterisations? e.g. cloud scheme? In Sect. 2.2., we added "Note that the other parameterizations (radiation, turbulence, shallow convection) also exchange heat in the atmosphere, but in a negligible way compared to cloudy processes." (see response to l. 86–88)

L383: provide some explanation for the rapid ascending trajectories. Mid-level convection is explained below, while low-level rapid segments occurring along cyclonic ascent are not further studied in the paper.

L388: quantify how much further the ridge extends west in REF. The difference looks quite small. Indeed, the difference is small, but still visible. We added "by about 100 km".

L401: is this region of conditional instability shown? Mention if it is or is not. When

we commented on Fig. 9b in Sect. 5, we added "They both lie in a region of vertically homogeneous θ_e values, which promotes conditional instability."

Technical comments:

L3: “structures of negative” should be “structures with negative”. Changed

L6 (and elsewhere): the authors should explain why the cyclone has been given this name. In the abstract this might not be possible so just saying “a cyclone” here and giving the cyclone its name in the main article may be best. We prefer keeping the name in the abstract, because the cyclone has also been described by other authors, and now explain its origin in the text.

L7-9: I would remove the sentence “The observations reveal...” as the abstract is quite long and this isn’t really necessary here. The sentence is crucial to highlight the rare observations and to introduce the double jet stream structure but has been shortened.

L9: change “reproduces well the observed” to “reproduces the observed”. Changed

L15: “near the bent back front” in what? The reference simulation? Yes because anticyclonic ascents are absent in the sensitivity experiment as explained in the previous sentence.

L17: remove “and” before “with the negative”. Removed

L17: thus appear → the convective cells thus appear. Changed

L17: add “the” before “negative PV bands”. Added

L27: reference to Martinez-Alvarado et al. (2018) here. They show Rossby wave amplitude still decreases in more recent NWP model configurations. We now refer to Martinez-Alvarado et al. (2018).

L31-32: change to “WCBs usually flow poleward and upward as coherent...”. Changed

L33: band → bands. Changed

L34: clouds → cloud. Changed

L34: During ascents → During WCB ascent. Changed

L35: which representation is → the representation of which is ... . Changed

L39: impact → impacting. Changed

L50: Add why the cyclone is named stalactite. We added "The cyclone was named after the low tropopause—which shape was reminiscent of a stalactite—during its intensification phase."

L106: Add sentence introducing the section and what will be included. We added "An overview of the cloud structures of the Stalactite cyclone and of the associated upper-level ridge is first given."

L116: along → above. Changed

L121: structures → structures present. Changed

L125: Change the sentence “REF reproduces well the ...” to “The track of the Stalactite cyclone is well reproduced in REF”. Changed

L128: meridian → meridional. Changed

L145: Highlight where these features are (see broad comment 3). See our response to broad comment 3

L147: 40W until z → 40W, reaching z... . Changed

L149: part → part of the domain. Changed

L158: except on → except in. Changed

L159: eastern part where it → eastern part of the domain where it... . Changed

L159: wind speed values → wind speeds. Changed

L162: simulation completes the description → simulation provides a complete description of... . Changed

L166: number ascents → number of ascents. Changed

L177: profile → profiles. Changed

L183-184: might be worth mentioning that the wind speeds in REF still tend to underestimate the observed peak wind speeds. We added "with the exception of slightly underestimated peaks.

L248: remove “a” before higher. altitude → altitudes. Changed

L252: remove “a” before strong. Changed

L255: remove the sentence “some start close to the surface”. Removed

L265: swap thereafter with “in the following section”. Swapped

L270: track → follow. Changed

L281: “the eastern part of the northwestern edge” is confusing to me. Consider rephrasing. The sentence is now: "In NODIA, the northwestern edge of the ridge and the PV tongue are shifted eastward compared to REF (Fig. 8b)."

L287: merge sentences here: NODIA. But → NODIA, but. Merged

L287: DIA → NODIA. Changed

L288: there → here. Changed

L299: what region is shown in Fig 9 a,b? The red box? We have erroneously referred to the brown circles in Fig. 6a. We now refer to the red stars which indicate the position of trajectories closest to the time shown in Fig. 9 a,b.

L327: remove “Thus”. Or join to previous paragraph. The paragraph has been attached to the previous one.

L359: is this dry air mass the cyclone's dry intrusion? No, that is why we called it "dry air mass", and not dry intrusion to avoid any misunderstanding.

L361: state what the tropopause fold is at the outer boundary of. Changed to "at the edge of the outer part."

L376: explain or motivate why the focus is on the WCB ascents. The sentence has been removed.

L391: Maddison et al. (2020) seems another appropriate reference to add here. Added

L401: "matches with the organised" → "matches the organised". Changed

L406: PV structures are → PV structure in WCB ascent regions are. Changed

References:

be consistent with journal abbreviations. Checked

L423: page and volume numbers missing. Added

Figures:

Fig1: add 'as' before '(a)'. Added

Fig1: What time are the MSLP contours in (b) and (c) shown? At the same time as the BTs. To avoid confusion, the sentence presenting the MSLP contours is now written in second position.

Fig4: mention that the profiles are shown for both observations and simulations in the caption. Information added

Fig5: if I understand correctly, the red box is used to select WCB outflow ascents? It is a bit confusing as I initially thought all ascents shown had to have passed through the red box at 11:00? Please clarify this in the text or caption. You understand correctly. In the caption of Fig. 5, it is written that "Spatial frequency [(now) number] of air parcels belonging to the ascents fulfilling the ascent criterion" and "the red box [is] the region where the ascents are selected at 11:00 UTC.".

Fig6: 40 trajectories are plotted, out of how many? Give the number in the text or caption. The number of trajectories is 220 000 for anticyclonic ascents and 250 000 for cyclonic ascents). This information is now written in the caption.

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