Authors' comments on the first revision of the manuscript: "On the cross-tropopause transport of water by tropical convective overshoots: a mesoscale modelling study constrained by in situ observations during TRO-Pico field campaign in Brazil", Reviewer-2

We greatly appreciate the reviewer's helpful and informative suggestions, which prompted us to revise our article. We appreciate your opinion of our English skills as well. To be honest, we are unable to undertake additional sensitivity tests to evaluate the differences between REF and NU21 runs due to the time and computational cost of these simulations, which necessitates additional time to analyse. Otherwise, we reran the simulations with a 30-second time resolution, which is critical for answering several of reviewer-1's questions. Here is where we record our point-by-point response to the reviewer's comments. The original comments of the reviewer are listed. Italic and boldface typefaces are utilised in the typesets. Each remark is met with a response from us. The phrase "adjusted" is always included in the response when any changes are made to the original version of the manuscript. The line numbers, page numbers, figure numbers, and table numbers refer to the original version of the document unless otherwise stated. The corrected version of the manuscript is also attached.

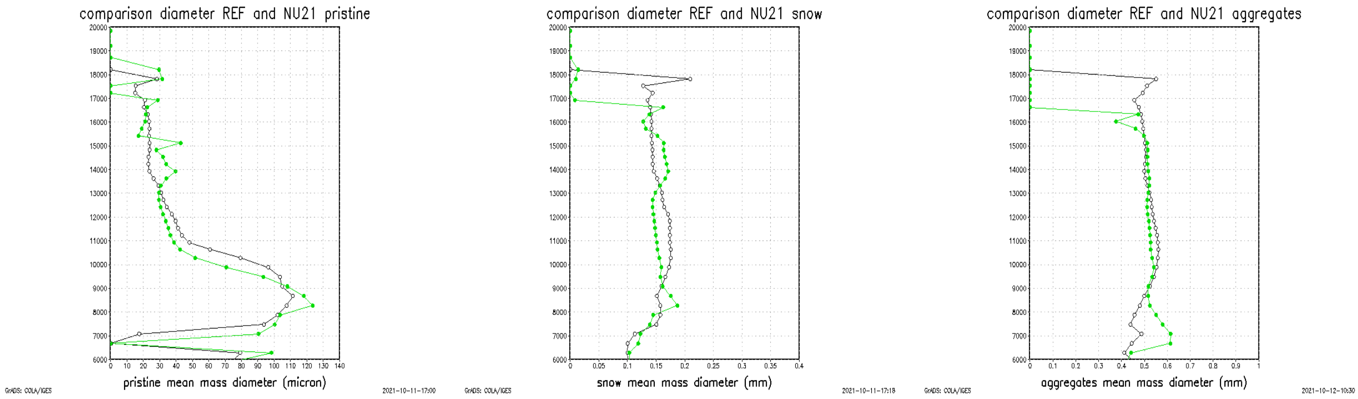
1 Major Comments

1. ***In regards to the nu21 simulation, can you describe what the change in the shape parameter from 2 to 2.1 actually means? The text says: A larger ν implies a larger modal diameter with a narrower distribution width. Please give quantitative values at least in regards to model diameter in the text and a sense of the distribution width?***

   adjusted - Please see Fig. 1 in the study by [Walko et al., 1995]. The paragraphs corresponding to line 155, on the other hand, have been revised to include more information on the shape parameter and the objective of employing NU21 simulation.

   The text is now: "In Eq. 1, f_{gam} denotes the probability density function for the modified gamma distribution of hydrometeors with a diameter of D, as obtained from [Walko et al., 1995]. $\Gamma(\nu)$ is the normalisation constant, and D_n is the characteristic diameter of the modified gamma distribution. A bigger ν indicates a narrower distribution width and a larger modal diameter. As a result, the proportion of smaller and bigger hydrometeors in the distribution is modulated. The size distribution of hydrometers would be more peaked as the modal diameter increased."

   Nonetheless, we have included a figure (#1#) that compares REF and NU21 mean mass diameter variability in altitude around overshoots for pristine ice, snow, and aggregates. As expected, NU21 has a slightly larger mean mass diameter than REF, at least for pristine ice, which is the first ice hydrometeor to be formed by freezing. Other hydrometeors have a more complicated conclusion because they arise from pre-existing ice particles. We should also emphasise that this comparison is essentially indicative; because the cells are not identical, they are not strictly comparable one to one.



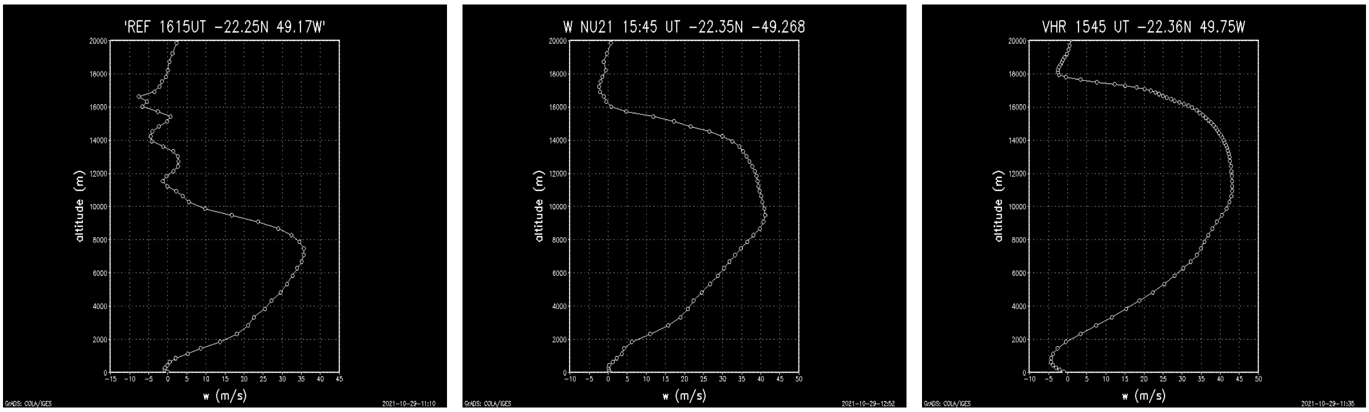
(a) Pristine (b) Snow (c) Aggregates

#1# Vertical profiles of mean mass diameters in the vicinity of overshoots for REF and NU21, respectively. The black lines are for REF at 16:15 UT, 22.0°S, 49.18°E. The green lines are for NU21 at 15:45 UT, 22.0°S, 49.2°E (almost the same position but not the same time). Those times correspond to the ones in Fig. 1 of the submitted paper. The positions correspond to the positions of the maximum overshoot in each case.

2. ***Why does the high vertical resolution simulation produce unrealistic results (too much convection)***

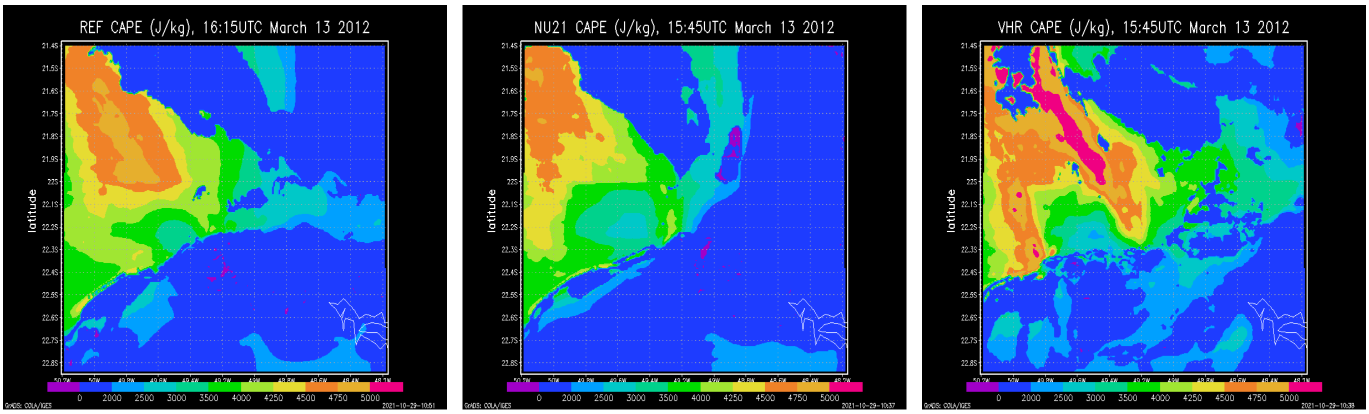
adjusted - We are surprised to see such deep convection behaviour in HVR run. We could not help ourselves when we observed the animation of cloud temporal progression compared to the S-band radar and the other two simulations. Exaggerated values in HVR could be due to unusually excessive convection, which includes extremely high upward velocity. Please see the attached figures on vertical wind (w) profiles (#2#) and CAPE maps (#3#) in the vicinity of overshoots, related to the Fig.1 in the submitted paper. Aside from that, we have expanded on other plausible explanations for such behaviour, such as the CFL limit and the need for Von Neumann stability testing in BRAMS. This is the first one we address because simulating HVR was somewhat difficult. Due to unexpected failures with no particular hint or reason for failure during the run, we had to make several history restarts to complete the simulation. The paragraph that corresponds to lines 261-269 has been changed.

The text is now: "To further understand the situation, one can expect HVR to determine more reliable dynamics across the tropical tropopause than REF and NU21, respectively. Contrary to expectations, it tends to intensify massive deep convection activity. A plausible fact to explain such behaviour in HVR is the ratio between vertical and horizontal grid points, which overestimates vertical motions due to grid cell saturation [Homeyer et al., 2014, Homeyer, 2015]. It might be the model's Courant–Friedrichs–Levy (CFL) limit, which in finite-difference simulation techniques constrains the relationship between infinitesimal increases in space grid points and infinitesimal time step increments. In the BRAMS model, the von Neumann stability assessment [Deriaz and Haldenwang, 2020] is necessary for the transport equations related to convection. Aside from that, Eulerian model simulations of high vertical resolution, high-frequency wave motions, such as inertial-gravity waves [e.g., Staquet, 2004, Young, 2021], can be overdetermined. As a result, they can exaggerate cloud microphysics [Aligo et al., 2009] and cause erroneous cloud conditions near the TTL [Jensen and Pfister, 2004]. Therefore, we leave HVR out of the next sections to describe the details, and we do not look at this simulation's water budget in the lower stratosphere."



(a) REF at 16:15 UT (b) NU21 at 15:45 UT (c) HVR at 15:45 UT

#2# REF (a), NU21 (b), and HVR (c) vertical wind profiles (w) in the vicinity of overshoots, respectively. The time and location of these vertical profiles are determined in accordance with the submitted paper's Fig. 1. It is worth noting that HVR has a surprising high velocity in the 16 km to 18 km altitude region, which is essentially non-existent in REF and NU21.



(a) REF at 16:15 UT (b) NU21 at 15:45 UT (c) HVR at 15:45 UT

#3# CAPE maps (J kg^{-1}) for REF (a), NU21 (b), and HVR (c), respectively. According to the submitted paper's Fig. 1, the time these maps are determined. It is worth noting that HVR has a rather high CAPE value, whilst REF and NU21 have almost none.

3. ***In Figure 7, the last panel is a water vapor flux. That is not a hydrometeor (as indicated by the caption). Is it just calculated based on vertical velocity and gaseous H_2O? The caption should indicate what is plotted.***

adjusted - Yes, the flux rates are calculated by projecting the vertical velocity against the normal to the isentropic level of 380 K. The isentropic level deformation caused by deep convection is taken into account. To do so, we compare the heights of surrounding grid-points in vertical grid coordinates in meters to determine the slope of the 380 K surface. It is worth noting that the δx and δy in this example is 800 m, which is the third grid's resolution. We take vertical velocity and the accompanying gaseous H_2O into account when calculating water vapour flux rates.

The figure caption is now: "The instantaneous domain-average mass-flux rate ($g\,m^{-2}\,s^{-1}$) of each hydrometeor and water vapour is illustrated in the third grid of the simulations for REF (green) and NU21 (blue). The cosine component of the vertical velocity with respect to the horizontal is used to determine the upward flux rate, which takes into account the slope at the 380 K level due to deep convection."

4. ***This figure confuses me; it could be made more understandable with a more detailed figure caption. Is the black line just the sum of the 5 hydrometeors + water vapor? What is ice? Is that just the sum of the 5 hydrometeors? And, what does it mean that the colors show the intensity of the event? Aren't you showing the altitude of the event as opposed to intensity? And, why does the plot start off with no water vapor in the region of interest? The caption (as well as the text) should say that this is a plot with respect to the unperturbed state. And, why doesn't the run go out any further in time? (as that is what is needed to assess how reversible the flux into the stratosphere was.)***

adjusted - Snow, pristine ice, graupel, aggregates, and hail have all been mentioned specifically in the figure description. The combination of these five hydrometeors is referred to as ice. Cloud top height replaces the perplexing word intensity. The cloud top height is shown by the colours and lengths of the arrows, while their placements represent the times of overshoot. Lines 430-435 have been updated in the paragraph. The unperturbed state was noted in the caption, and it is also referenced in line 430 of the text.

The caption is now: "Water mass budget (ice and water vapour) for (a) REF and for (b) NU21 in the third grid between the 380 K to 430 K isentropic levels. The ice budget contribution includes the five ice hydrometeors (pristine ice + snow + aggregates + graupel + hail). The colour and length of the arrows indicate the cloud top altitude of each occurrence, with the smallest arrows (brown) referring to cloud top heights of 17 km to 18 km, the intermediate-sized arrows (green) relating to cloud top heights of 18 km to 19 km, and the largest arrows (magenta) corresponding to cloud top heights greater than 19 km."

Of course, the runs continue past 17:30 UT. Please see the animation on cloud top heights with S-band radar in the Supplementary Materials. When there is no convective activity in the model, we consider it as an unperturbed condition in the runs. The water vapour profile reaches a near plateau profile near the end of the mass estimation period, i.e., 17:30 UT in both runs, while the ice (sum of 5 hydrometeors) profile shows a descending trend - no more deep convection, indicating that ice is sublimating or possibly falling back into the troposphere and besides we observe a rise in water vapour budget. If we look at the simulations over a longer period, we can see that more overshoots are induced. The corresponding flux rates are shown in Fig. 7. At about 17:30 UT, both simulations reveal almost no entrance of hydrometeors and water vapour at the 380 K level. In Fig. 8, we plan to calculate the mass budget associated with individual overshoots. In regard to your point about reversible fluxes, we include a range of values from the near plateau at the end of the observation period to allow for the possibility of ice falling down to the troposphere rather than sublimating locally. However, it is not possible to directly compute the sedimentation flux through the tropopause in the model since it depends not only on the vertical wind velocity but also on the fall speed of each hydrometeor. It would have required rewriting BRAMS' microphysical framework, introducing extra scalar variables, and rerunning all of the simulations reported here, which was not feasible given the time constraints.

5. ***Conclusion 3 says: "It further indicates that the rest of the 32% ice (principally pristine ice and snow) progresses further up in the stratosphere." Was the model run long enough***

to verify this?

adjusted - This estimate is based on simulations till 17:30 UT. The complete simulations, on the other hand, ran until March 14th at 12:00 UT. You may refer to line 184 for further information. We have until March 13th, 22:00 UT to validate our models using the S-band radar. Also, at 18:53:38 LT (UT-3 hours), there were no more echoes on the radar screen, indicating that all convective activity had ceased within a 100 km radius. Nevertheless, the simulations appear to be active in producing deep convection until 18:45 UT, which is not the case in radar images in the nearby area of Bauru, according to the animation of the radar versus model comparison of cloud tops. Moreover, Table 1 should be consulted. Based on the existing analysis, it is difficult to say whether snow and pristine ice still exist in the dome's higher layers. However, because the fall speed of these two hydrometeors is so slow, it has been ascertained that a situation in which a considerable amount of them fall back to the troposphere before sublimating is extremely unlikely. Otherwise, we have rewritten the third point in the conclusion to avoid any misunderstandings. We place emphasis on the fall speed of pristine ice and snow, implying that they have a very slight possibility of falling back to the troposphere.

The text is now: "#3. Within the modest layer of 380 K to 385 K, 68% of the overall ice mass exists. It also suggests that the remaining 32% of ice (mostly pristine ice and snow) moves higher in the stratosphere. Because of the very slow fall speed at altitudes above 385 K and the subsaturated conditions with respect to ice, that 32%, which is pristine ice and snow, is anticipated to stay in the stratosphere and sublimate."

6. ***Conclusion 4 says "For this case study, a single overshooting plume injects about 4.15 kt of ice above the 380K level." Where does this value of 4.15 kt come from? Is this an average of the two model simulations? If I then apply Conclusion 3, which seems to say that 32% is irreversibly injected into the stratosphere, then I get close to the 1.34 kt noted as the minimum in the upper limit range noted.***

adjusted - Yes, the ice injection values from the two scenarios are averaged. We have clarified it now. Also, thank you for your observation about the ice budget; it is precisely how you see it. Points 3, 4, and 5 have been modified in the conclusion.

The text is now:"#4. A single overshooting plume injects around 4.3 kt of ice in REF and 4.0 kt of ice in NU21 over the 380 K level in this given scenario in Bauru, with NU21 injecting slightly less ice than REF as expected. #5. The stratospheric WV enhancement due to one overshooting event is estimated to range between 1.34 kt to 2 kt as the upper limit and 0.34 kt to 0.75 kt as the lower limit after sublimation and (or) sedimentation of the stratospheric ice. If we consider complete sublimation of ice, as in REF, it confirms our estimate that the 32% of 4.3 kt of ice irreversibly traveling further up to the stratosphere results in the stratosphere having the lowest hydration in the upper limit range."

7. ***In regards to the calculation of the lower limit, is that just making an estimate based on what is water vapor at the end of the simulation? And, another question, why is the ref simulation 2.5 hours, and the nu21 simulation 3.5 hours? Isn't the amount of water vapor at the simulation end going to be a function of how long the simulation actually was?***

– Yes, our lower limit for H_2O injection into the stratosphere is the scenario in which all of the ice particles have sedimented, so the remaining H_2O in vapour form provides the lower limit. And this is not the total vapour until the end of the simulation; it is still 17:30 UT, as previously discussed. Both runs reach a plateau above the 380 K level around 17:30 UT. The runs, however, end at 12:00 UT on March 14th. Your question about the observation period in REF and NU21 is perfectly valid, and we have thought about it as well. To avoid such uncertainties, we consider the simulations from a time point where both are in the same stage, i.e., the unperturbed state with respect to convection activity. REF needs only 2.5 hours to achieve a stable state in terms of water vapour budget above a 380 K isentropic threshold, whereas NU21 takes 3.5 hours. Finally, your assessment of the duration of the run and water vapour enhancement is correct; NU21 accumulates approximately 3 kt of water vapour, which is relatively higher than REF. However, the criteria for estimating the mass budget for both REF and NU21 runs are the same.

8. ***This seems to be results for a specific meteorological event, and not necessarily extractable to a general case, so I question the final conclusion that this study provides "a road map to upscale the impact of overshooting convection on the stratospheric water vapour at a continental scale."***

   adjusted - Thank you for pointing this out. These findings do not imply that this is a common occurrence. However, more case studies like this one are required to develop a global picture of overshoots utilising cloud-resolving simulations from various locations. This reported study is the consequence of many overshooting domes reaching different elevations above the 380 K isentropic layer, despite the fact that it is a single-case study. In that way, it also accounts for the variation under hydration induced by overshoots of varying intensity - the cloud top height, even when they occur in similar circumstances (e.g., stratospheric humidity). Otherwise, the lines between 495 and 515's corresponding paragraphs have been changed.

   <u>The text is now:</u> "This paper describes several cloud-resolving simulations of convective overshoots penetrating the lower stratosphere using the BRAMS mesoscale model, corresponding to an observed case on March 13, 2012, during the TRO-Pico field campaign in Bauru, Brazil. During this series of overshooting convection events, several plumes reached the stratosphere. As a result, it accounts for the hydration heterogeneity produced by overshoots of variable intensity, even when they occur under similar circumstances (e.g., stratospheric humidity). The S-Band radar stationed at Bauru, as well as the balloon-borne measurements from this campaign, allow the simulation results to be validated. These simulations, which have been validated as realistic when compared to TRO-Pico measurements, are then used to obtain the main physical characteristics of overshooting plumes.

   These data can be utilised to develop a nudging method that quantifies the influence of overshooting convection on the stratospheric water vapour using a low-cost, large-scale simulation. Though the findings are limited to a case study in Brazil and may not be generalisable, more of similar case studies should be conducted in order to gain a better knowledge of the events, and this work is in keeping with that goal. This instance would be the next stage in the current research, offering a road map for extending the impact of overshooting convection on stratospheric water vapour on a continental (Brazilian) scale."

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