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Atmospheric Chemistry and Physics
Discussions

Interactive comment on "Simulation of convective moistening of extratropical lower stratosphere using a numerical weather prediction model" *by* Zhipeng Qu et al.

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Page 1, line 4: Maybe add here Riese et al. 2012. They showed also how small change in water vapor due to mixing processes change the radiative budget of the UTLS.

Reference added.

Page 2, line 24: Isentropic transport of water vapor due to planetary wave activity is also an important transport mechanism for transporting tropical tropospheric air into the lower extra-tropical stratosphere (see e.g. McIntyre and Palmer, 1983; Waugh, 1996; Homeyer and Bowman, 2012). I recommend to include this mechanism also in

the manuscript to complete all transport pathways.

Thanks! It's added into the manuscript.

Page 2, line 33: I recommend to add the paper of Lee et al., 2019. They performed also high-resolution model simulation of an overshooting event in the Asian monsoon region and showed how the moistening occurred and how the hydrated air was transported in the lower stratosphere.

Reference added.

Page 4, line 34: In summer times the standard value in the extra-tropical lower stratosphere is more 5 ppmv (see Zahn et al. 2014 Figure 5). I would recommend to change the text from 4 to 5 ppmv.

Done.

Page 6, line 21: Here you state the time of Fig. 4 to be at 19:49. In the figure caption it is stated 19:46. Please correct one of these times.

Correction is done. The correct time is 19:46 UTC.

Where there any cloud instrumentation aboard the ER-2 for measuring cloud number concentration or IWC? If yes, did you check if there were still ice crystals present at flight altitude in the domain B. That would be interesting to see, because than the ice crystals would have been transported over a longer distance in the stratosphere. This transport is shown by the Lee et al. 2019 and it would be interesting to see, if it occurred also in your case.

Good point! We have checked the ice water content for the ER-2 flight within domain B. There are some areas we found the presence of ice with the IWC between 1x10-6 and 1x10-3 g/m3 at lower altitudes between 14 and 15.5 km below the tropopause level. Fig. 1b shows the ice water content observed by the aircraft. The horizontal locations of these ice are marked by red dots in Fig. 2 on the aircraft path (gray line). We traced the air parcels in the northern part of domain B from the altitude of 14 km back to 04:00 UTC when a more recent convection is happening in domain A. Particularly, the ice seen in the northeast part of domain B can be linked to the convection event as highlighted by the red trajectory. The back-tracing properties of this parcel are shown in Fig. 3. We can find that the formation of ice is near 04:00 UTC due to the convection (Fig. 3e). During the next 8 hours, the air parcel are slightly super-saturated (Fig. 3d). Therefore, the loss of ice is not due to the sublimation but the falling of ice to lower altitude. Near the time of 12:40 UTC, the relative humidity with regard to ice falls to below 1. All the remaining ice is quickly sublimated within about half an hour. Nevertheless, the ice is then reforming near 13:40 UTC due to the slow ascent of air with decreasing temperature and increasing relative humidity. The ice shown in Fig. 2 for the highlighted parcel is therefore not the ice originally formed during the convection, but formed later during the ascent of air about 6 hours before. We can also observe the impact of the dehydration due to the formation and the falling of ice near 15:40 UTC with a decrease of water vapor mixing ratio of ∼20 ppmv.

Similarly, in the GEM simulation even in a higher altitude above the tropopause we still found this formation of ice although with smaller ice water content (in the order of ∼ 1x10-5, see updated Fig. 8 in the manuscript). The origin of the humid air parcel is often linked to the convection that happened before. In the case of Fig. 8 (manuscript), it is the convection started from 25 Aug in the simulation. Since the formation of ice in higher altitudes above tropopause is much less significant than in lower altitudes. Contrary to the dehydration effect in Fig. 3 near 15:40 UTC, we didn't find a significant impact of dehydration in high altitudes (e.g. Fig. 8 of the manuscript). Therefore, this will not change our conclusion by linking the water vapor injected in domain A with the simulated/observed water vapor in domain B for the altitudes above the tropopause.

Some new texts are added into the manuscript, the Fig 2 and 3 here will be added to the SI materials:

"One particular note for Fig. 8 is the formation of ice shortly after 19:40 UTC 27 Aug

when the humid air parcel slowly ascends with decreasing temperature and increasing relative humidity with regard to ice. At these altitudes, the ice water content is relatively low (∼1x10-5 g m-3). The ice particles will gradually fall to a lower altitude and eventually be sublimated again. This process will partly dehydrate the upper layer of the atmosphere where the ice is forming, and later hydrate the lower atmospheric layer through ice sublimation. However, this dehydration has minor impact for the air parcels above the tropopause. We observe that the water vapor mixing ratio of the air parcel at the 15.5 km altitude (i.e., the upper layer) increased slightly after 19:40 UTC (Fig. 8a). This might be the results of the mixing with the adjacent air in the northeast side of the parcel which is more humid (pointed by the black arrow in Fig. 7). Due to the limited impact of dehydration through ice formation above the tropopause, our interpretation of linking the stratospheric water vapor injected in domain A and water vapor simulated/observed in domain B is therefore not affected in a significant way by the ice formation process."

"For the atmospheric layer under the tropopause between the altitude of 13.5 and 14.5, the horizontal wind speed increases significantly. The back-tracking results show that the humidity and ice field in the northern part of Domain B are linked to the convection initiated at the beginning of 27 Aug in domain A. The locations of ice water content in domain B from the simulation partly agree with what are observed by the aircraft in Fig. 2b. Based on the back tracing results, we noticed that the ice in Domain B is not originally formed during the convection, but later during the slow ascent of the humid air parcel. This is similar to the hydration/dehydration process discussed above but at a lower altitude below the tropopause. The ice formed at this lower altitude is more abundant (in the order of 1x10-3 g m-3). The impact of dehydration (ice formation and falling) at this level is significant which can be seen in Fig. SI.3 near 15:40 UTC with an amplitude of about 20 ppmv. The readers are referred to the supplementary materials for more discussions on this topic (Fig. SI.2, SI.3)."

Page 9, lines 5-10: Maybe it is worth a mention that the averaging kernels of limb sounders like MLS smear out the strong vertical gradient in water vapor at the tropopause (Hegglin et al.,2013).

Added to the manuscript.

Page 9: The comparison between GEM and MLS is not really done in a balanced way. The difference is partly larger (> 100%) than the biases which are reported in the literature. These strong differences can be hardly explained by just mentioned the possible bias of MLS water vapor. It could also be a result of the model simulation. For example, warmer temperatures in comparison to MLS could lead to slower ice crystal growth and thus less dehydration and thus higher gas-phase water, which could be transported into the lower stratosphere.

Thanks, this is a very good point! We modified the text as follow:

“We applied the averaging kernel of MLS on the mean profiles of GEM simulated humidity and temperature within the 100x100 km regions centered on the MLS footprints. The comparison here suggests that both model simulations give higher estimations of water vapor content in the UTLS comparing to MLS retrievals, although the higher-resolution simulation better approximates the satellite observations. It is also found that GEM slightly overestimated the temperature comparing to MLS retrievals. This suggests that warmer temperatures in comparison to MLS could lead to slower ice crystal growth and thus less dehydration and thus higher gas-phase water. The spatial-temporal errors of the model simulation, e.g. shifted convection area, and time, etc., might also contribute to the discrepancies between the GEM and MLS profiles. Further, the lower value of water vapor content from MLS near the level of 160 hPa may be subject to the aforementioned negative bias in the MLS data.”

The averaging kernels of MLS are applied to the GEM profiles for a more suitable comparison. The Fig. 6c and 6d of the manuscript are modified accordingly.

Can you please comment on the following questions and suggestions? Which Version

of MLS data are you using (this would be also nice to mention in the text)?

The version used in this study is v4.2. We added this information to the manuscript.

Did you apply the averaging kernels of MLS onto the GEM profile? Otherwise a fair comparison is barely possible. Why not using the exact location of MLS and applying the averaging kernels?

The averaging kernel was not applied in the original version. We added the comparison applying the averaging kernel in the updated version (see answers above). This does not change the comparison results or any conclusion.

Why are the profiles of water vapor (panel a/c/e) and also temperature (panel b/d/f) so different? They should both represent air masses moving from domain a to domain b as shown by the trajectories. It seems that the situation is strongly variable. Can please discuss in the text about the standard deviation of the mean profiles to get a better feeling on the variability.

One factor causing the differences in profiles is that there is a slow but persistent vertical movement of air as shown both in Fig. 8c in the manuscript and Fig. 3c in this response document. This will change the form of the profiles. For example, the ‘bump’ in humidity profile in Fig. 6a (manuscript) is at the level of 16 km, while it moves to 16.7 km in Fig. 6e (manuscript) which is coherent with the slow ascending motion. Other factors such as the large circulation, radiative heating/cooling and the significant differences in latitude which results a warmer tropopause temperature in the north (domain A) and a cooler one in the south (domain B) (Fig. 4).

For better understanding of the deviation between GEM and MLS, I would also recommend to add the location of the MLS profile also into the map in Figure 7.

Done

Figure 8: You show some parameters of an individual trajectory in this figure. The water vapor amount with ∼20 ppmv is quite high and the temperatures are cold between

203-206K, which could create conditions with supersaturation wrt ice. and therefore, additional ice formation. Do you see any signs of ice formation in the lower stratosphere along these trajectories? This could be important, because it could partly dehydrate the previously hydrated air masses.

For this particular air parcel, the formation of very thin ice does happen during the ending hours. More discussion is added into the manuscript for the dehydration effect by the formation of the ice (see the answer above). The ice water content and relative humidity are added to the Fig. 8 in the manuscript.

Page 10-11: For me it is not clear, which part of the equation 5 account for ice sublimation/transport? Because in the equation only q, which stands for water vapor, is considered. Can you please better explain how you estimated the change due to advection and ice sublimation as stated in lines 16-20.

We clarify that the equation is used for analyzing and understanding the direct transport. In the manuscript, we try to use the Reynolds decomposition to investigate the importance of injection due to gravity wave breaking with regard to the direct transport only. We argue that for the high-resolution simulation, the majority of the direct transport is linked to the gravity wave breaking. Ice sublimation is therefore not taken into account in Eq. 5.

Page 12-14: Where does the sublimation occurs in the high-resolution models? Is it directly in the overshoot or are the ice crystals first mixed into the lower stratosphere by wave breaking and small-scale mixing and then sublimate? Which brings me to a further question, if ice crystals are transported along the trajectories in the lower stratosphere? Perhaps, you can add this information also into the manuscript.

In the high-resolution simulations, ice was firstly brought to the lower stratosphere within the cloud overshooting tops. There the ice cannot be sublimated efficiently. During the fall of the overshooting top the gravity wave breaking happens, a fraction of ice in the overshooting top will be brought into lower stratosphere in an irreversible way (no

downward movement to bring then back to troposphere, only relying on sedimentation). Further, the humid air transported into the lower stratosphere might be supersaturated depending on the temperature of the reached altitude. This will be a second contribution to the ice plume. These plumes will gradually be sublimated through mixing with dryer air or be sediment to a lower altitude. In our simulation at 1.0 km grid-spacing, these plumes will not last for a long time (generally less than 1 hour) before they disappeared completely near the convective zone. We added the description for ice staying in lower stratosphere in the manuscript:

"Ice plumes are also formed near the areas where the gravity wave breaking happens. Two sources are found: the direction transport of ice and the formation of ice under supersaturation condition within humid plumes. The sizes of ice plumes are generally smaller than those of the water vapor plumes, because ice will be completely sublimated/sediment within a short period of time, generally within one hour."

Page 13/14: What does a negative sublimation tendency mean? I would guess it is additional ice formation or particle growth. Or is it both?

The notion 'sublimation' presented in the manuscript denotes the dynamical effect of both ice sublimation and vapor deposition. The negative value signifies that the vapor deposition is faster than the ice sublimation, hence dehydration. We realize that the use of 'sublimation' in might cause confusion. Additional explanation is added to clarity the definition of sublimation:

"Ice sublimation (hydration) and vapor deposition on ice (dehydration) are two opposing microphysical processes competing for dynamical balance. We use hereinafter 'sublimation' to denote the combined effect of these two processes. The positive value signifies that the ice sublimation is faster than the vapor deposition, and the negative value signifies the other way around."

Page 14: I agree with your conclusion that ice sublimation occurs less pronounced in the high-resolution model because of existence of ice crystals mostly in the overshooting core. In the relative humidity distribution (Figure 12 b) I would expect higher fraction of IWC in the sub-saturated region (Rhi < 1) for the low resolution compared to the high resolution, if there is a much higher sublimation rate. Do you have an explanation for the agreement of IWC distribution in sub-saturation for all three model setups?

In 10 km simulation (Fig. 11d and 11g of the manuscript), we can find that the majority of the ice at this altitude is located in an area of slight supersaturation (rhi $\sim$1.09). This means that the majority of the ice is not sublimating, but slowly growing by vapor deposition. This can be seen in Fig.11a (manuscript) that in the cloudy area the vapor deposition is happening although with slow rates (light blue area). The areas where we find high ice sublimation rates are near the northern edges of the cloudy area due to the mixing with the dry stratospheric air. These areas have an important contribution for the mean sublimation rate in the domain A, and their relative humidity tends to be sub-saturated, although their ice mass fraction in domain A is not significant. This can be one of the reasons why in Fig.12b (manuscript) the majority of the ice is slightly supersaturated rather than sub-saturated.

Another important factor is the way GEM calculates the dynamic and physical processes. At a given time step, GEM calculates the dynamic processes first (advection, etc.) and then the physical processes (microphysics, etc.). After the dynamic calculations, the sub-saturation should be very pronounced on the edge of the cloudy area, but the properties are not saved until the physical processes are finished which reduces quickly the sub-saturation due to the sublimation. Considering that in the 10 km simulation the time step is set to 5 min which is long enough to reduce the sub-saturation produced by the mixing with dry stratospheric air (dynamics).

Technical comments/suggestions: Page 8, line 8: Citation should be Vömel et al.

Done

Page 14, line 9: It is more common to use the term supersaturated instead of oversaturated.

Done

Figure 2: Can you please include the date of the ER-2 measurements into the figure caption.

Done

Figure 4: The comprehensibility of the vertical wind speed in panel d would be better, if you choose a color scale centered with the color white at the value of 0 and with positive/negative values in two different colors (e.g. red and blue).

Done

Figure 5: Same suggestion above for panel c and d.

Done

Figure 12, caption: "relative humidity" instead of "relatively humidity"

Done

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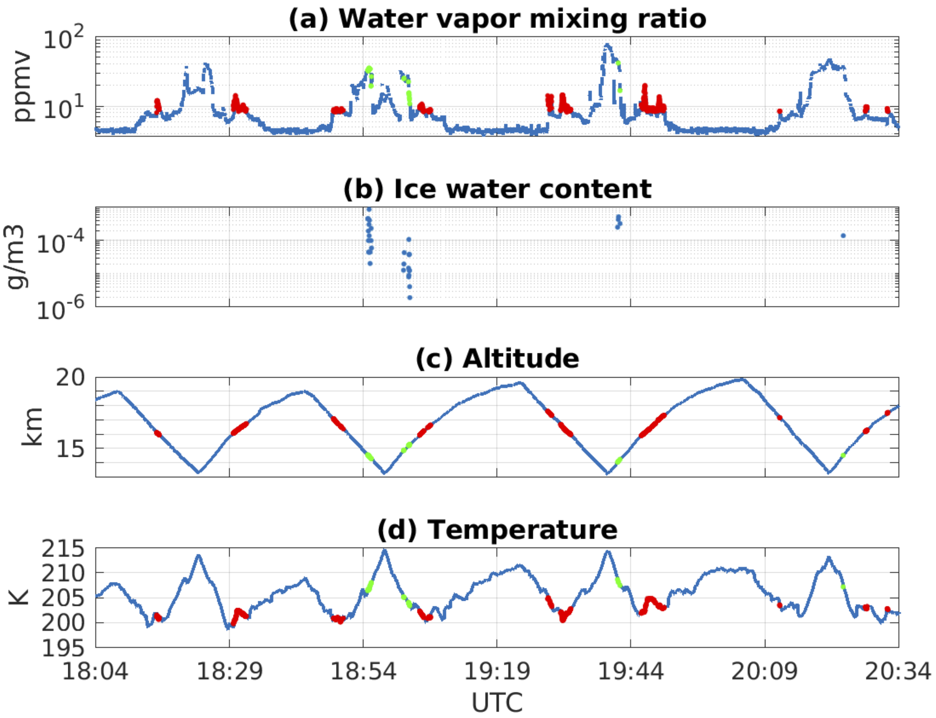

Fig. 1. ER-2 aircraft observation of a) water vapor mixing ratio, b) ice water content, c) altitude and d) air temperature in K, on 27 Aug 2013. Green dots: ice observed.

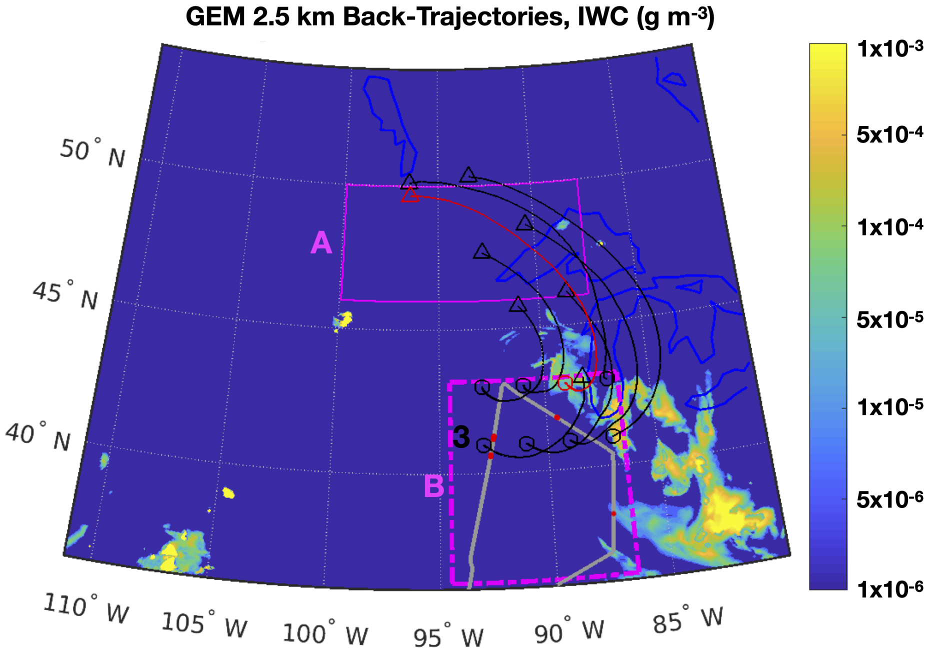

Fig. 2. Background: ice water content (∼14 km, 1940 UTC 27 Aug); gray line: ER-2 aircraft path (red dots: ice); circles: starting points at 19:40 UTC; triangles: ending point at 04:00 UTC.

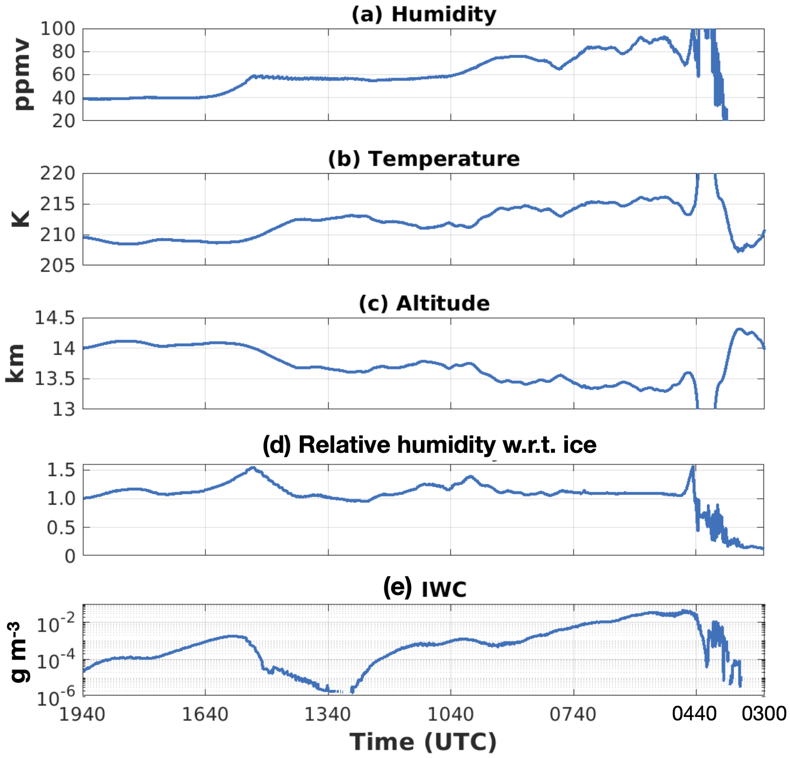

Fig. 3. The changes of the properties of the highlighted air parcel in Fig. R2 along its back trajectory from 19:40 UTC to 03:00 UTC 27 Aug.

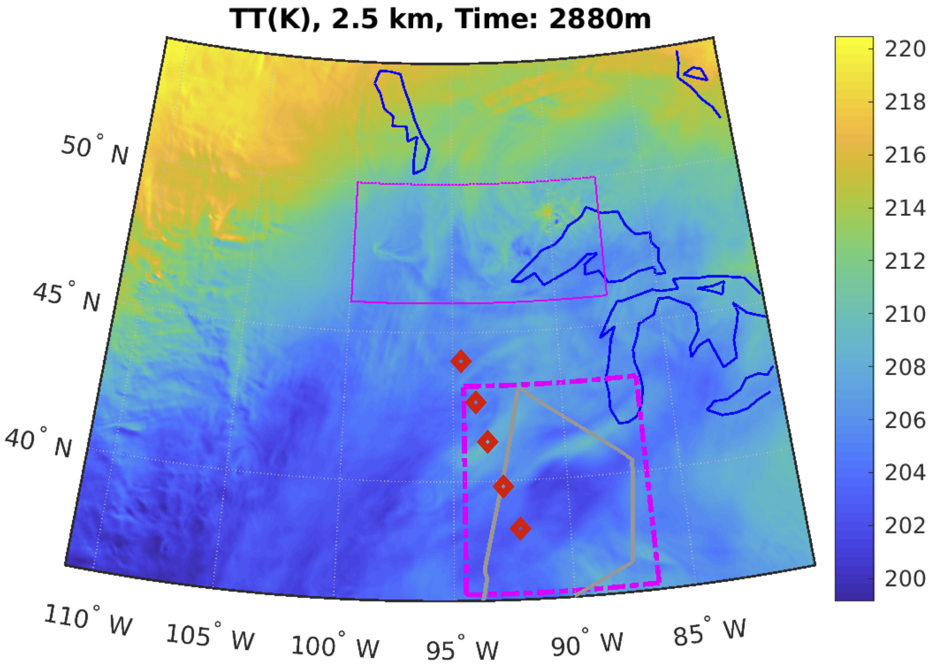

Fig. 4. The temperature field at the altitude of 16 km, at 23:00 UTC 25 Aug. Magenta solid line: domain A (profile a/b); magenta dash-dot line: domain B (e/f); red diamonds: MLS footprints (c/d).