Convective hydration in the tropical tropopause layer during the StratoClim aircraft campaign: Pathway of an observed hydration patch

By K. O. Lee et al.

Reply to the referees' comments

In the following, the comments made by the referees appear in black, while our replies are in red, and the proposed modified text in the typescript is in blue.

Referee #1 comments

Summary general Comments

This study examines the origins of an observed moisture patch to the south of Kathmandu, Nepal during the StratoClim campaign in 2017. The analysis was done using aircraft measurements, along with satellite observations and a large-domain Meso-NH convection-permitting simulation over 3 days to determine the source and evolution of the patch throughout its journey prior to being observed over northern India. Overall, this study shows overshooting convection hydrating a sub-saturated lower stratospheric region. While it is important to document a realistic case study, there are several queries that I would like the authors to address before this study can be considered for publication. These mainly related to the discussion of processes that govern the evolution of the hydration patch along its trajectory. The overall impression that I get is that the net moisture content of the advected plume decreases over time because of further mixing with tropospheric air, which is argued to dilute the patch along its journey. However, the authors do not show the time evolution of the mixing along the pathway and fail to systematically discuss the important role of ice microphysics in regulating the humidity of the patch within the moist layer (ML), specifically via the 'vapour scavenging' effect of ice.

We appreciate the time and effort you put in this review as well your mindful comments on our paper. We have worked hard to discuss clearly about the processes governing the evolution of the hydration patch along its trajectory. In particular, we include the discussion about the important role of ice microphysics. Replies to each comment are listed below.

Specific Comments:

Tracking the enhanced moisture patch over northern India back to Sichuan Basin, China. I would suggest to the authors that they do an offline HYSPLIT back-trajectory analysis with their hourly simulation results. In my mind, this would really help to confirm that the observed moisture patch/layer was indeed coming from where the authors state the overshooting convection was happening. I found it hard (and other readers may too) to visually track or 'chase back' (L160-161) what is plotted in Fig. 4 and reconcile with what is shown in the satellite images in Fig. 5. There are also other locations that appear to show overshooting tops (e.g. Fig. 5g, h). In other words, how do we robustly know that this is the same advected plume that originated over China from overshoots along the way to northern India? The lat/lon extent in Fig. 4 is also smaller than Fig. 5. I would suggest the authors either expand Fig. 4 to match the lat/lon dimension of Fig. 5 or draw a box in Fig. 5 denoting the extent of Fig. 4 to help orientate the reader.

In addition, it would be useful to draw wind vectors and pressure contours on the 410 K isentropic surface shown in Fig. 4. This would help the reader get a sense of the synoptic upper-level flow that would be steering the enhanced moisture patch from the purported source in China towards northern India.

For the sake of clarity on the pathway of the hydration patch from the Sichuan basin to the south Kathmandu, we have i) joined here the 2-hourly images of the hydration patch for 1.5 day, ii) added horizontal wind vectors on Figure 4, and iii) marked the domain of Fig. 4 in each panel of Fig. 5.

i) Figure A shows the 2-hourly images of the hydration patch from 14:00 UTC on 6 August to 06:00 UTC on 8 August.

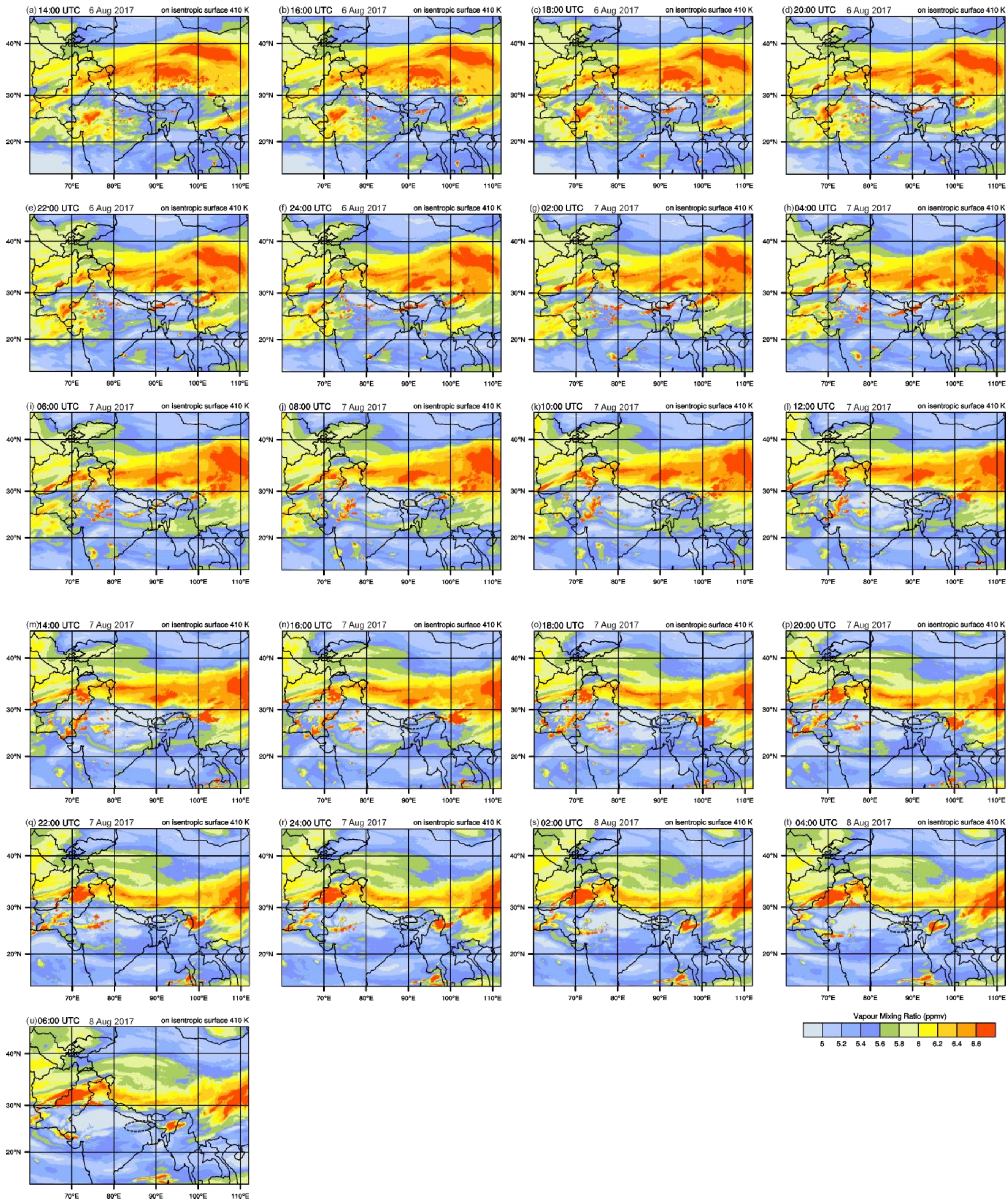


Figure A. Horizontal distributions of water vapour at 410 K isentropic altitude every 2 hour from 14:00 UTC on 6 August to 06:00 UTC on 8 August 2017. The target hydration patch is marked by an ellipse with dashed line.

The figure demonstrates that the injected water vapour at 14:00 UTC to the TTL over the Sichuan basin (pointed by an arrow and circle, Fig. Aa) travelled toward the west-southwest, to the south Kathmandu at 06:00 UTC on 8 August (ellipse, Fig. Au). For the sake of clarity, the description about the hydration patch has been further improved in the manuscript.

♣ Page 6, lines 160–164

"[…] The hydration patch is chased visually back in time every hour from 06:00 UTC on 8 August to 13:00 UTC on 6 August 2017, considering the prevailing wind direction and speed at 410 K isentropic altitude. At 14:00 UTC, a large amount of water vapour (≥ 6.6 ppmv), that is injected by the convective overshoot in the Sichuan basin, starts to appear at this altitude, generating a hydration patch. With the dominant east-northeasterlies (15−20 m s^{-1}), it travels to the south of Kathmandu."

ii) Figure 4 has been improved joining the horizontal wind at the altitude of 19 km (nearly equivalent to 410 K isentrope) at 06:00 UTC on 8 August. The dominant wind is east-northeasterlies at the speed of 15–20 m s^{-1}. The wind direction corresponds to the pathway of the hydration patch from the Sichuan basin to the south of Kathmandu. During 14:00–21:00 UTC on 6 August, the hydration patch moved westward with weak easterly wind (about 10 m s^{-1}). Then during 00:00–06:00 UTC on 8 August, the hydration patch moved farther southwest, to the south of Kathmandu with the strong east-northeasterlies (about 25 m s^{-1}).

♣ Page 26

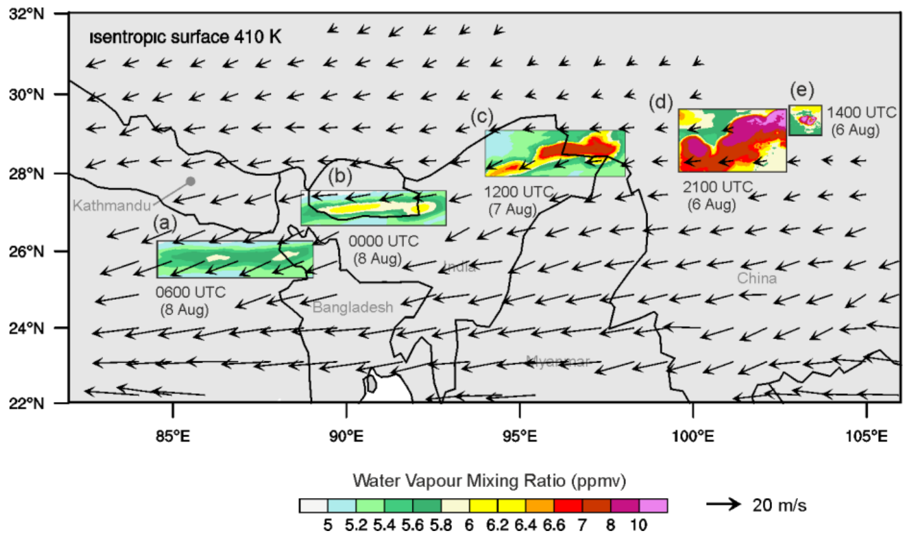


Figure 4. Target moist patch. Horizontal distribution of water vapour mixing ratio at 410 K isentropic altitude at (a) 06:00 UTC, and (b) 00:00 UTC on 8 August, (c) 12:00 UTC on 7 August, (d) 21:00 UTC and (e) 14:00 UTC on 6 August 2017. The horizontal wind at the altitude of 19 km (about 410 K isentrope) at 06:00 UTC on 8 August is displayed by vectors.

iii) As suggested, the domain of Fig. 4 is marked by a box in each panel of Fig. 5. And the target convective system is pointed by the white arrow.

♣ Page 27

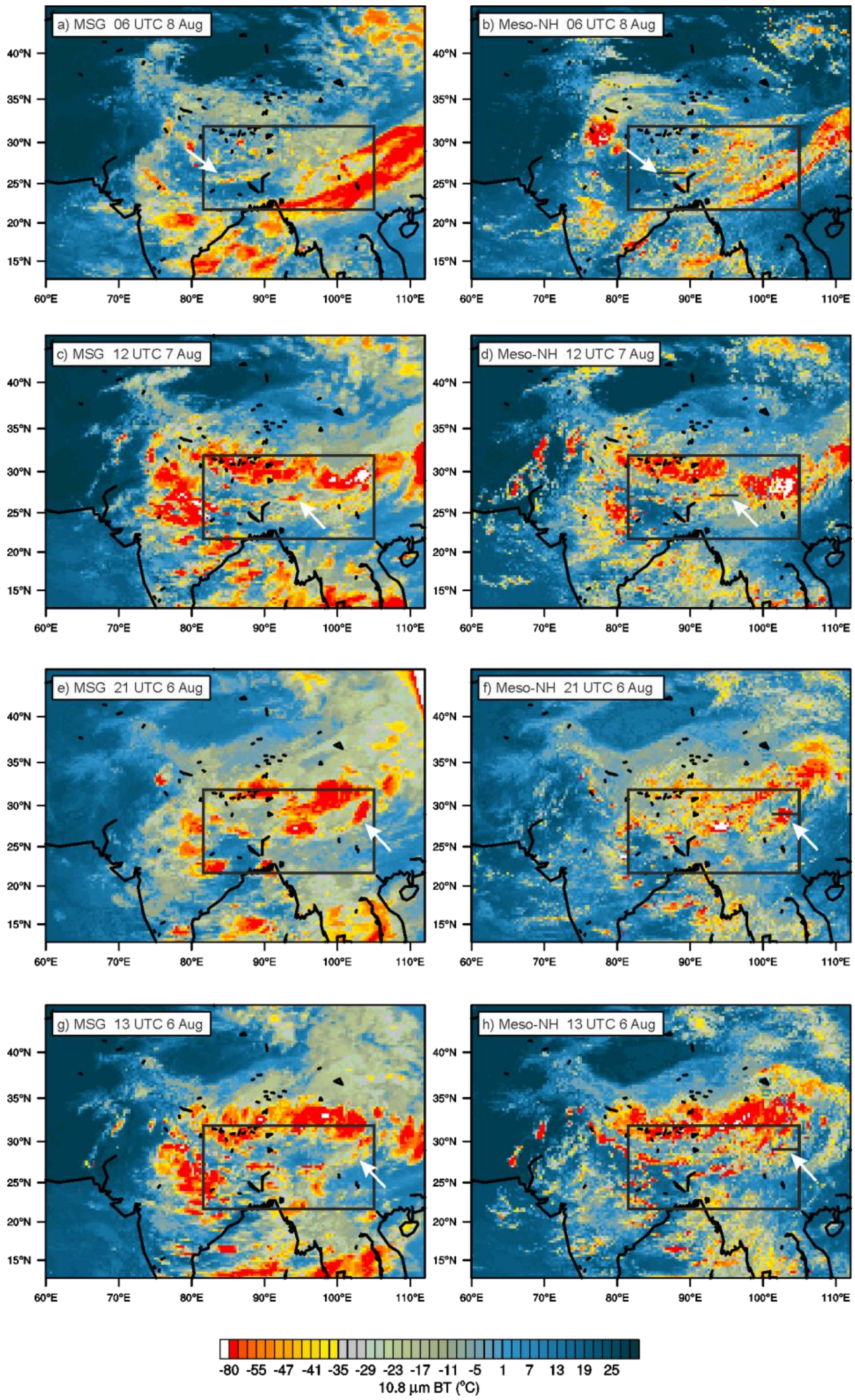


Figure 5. BT 10.8 µm obtained from SEVIRI/MSG (left) and Meso-NH (right) at (a)−(b) 06:00 UTC on 8 August, (c)−(d) 12:00 UTC on 7 August, (e)−(f) 21:00 UTC, and (f)−(h) 13:00 UTC on 6 August 2017. The domain used in Figure 4 is marked by a box in each panel, while the location of vertical cross-sections used in Figures 6−9 is marked by a black solid line in the right panels. The location of hydration patch is depicted by the white arrows.

Tracer implementation and parcel origin of the enhanced moisture patch

I found the implementation of the tropospheric tracer in the model study too simplistic. Specifying 1 for tropospheric air below the 380 K level and 0 above results in sharp vertical gradients near the boundary. This is what you see in Fig. 8a and Fig. 10a at 13 UTC 6 Aug. These sharp gradients would then be by numerically diffused over the course of the model integration, thus what you get is likely to be dominated by artificial smoothing and not by physical turbulent mixing, once the convective overshooting is over and the perturbed isentropes return to equilibrium (Fig. 8h-l). In addition, the formulation of the tracer makes it hard to properly distinguish whether the residual tracer amount came from lower, middle or upper tropospheric/TTL air. This is important in the context of understanding the nature of the vertical transport coming from overshooting convection. I think this is a caveat/shortcoming that should be acknowledged by the authors in their subsequent discussions in the text involving any reference to tracer concentrations.

For comparison, Hassim and Lane (2010) showed that their simulated enhanced moisture plume from overshooting convection in the tropical lower stratosphere was composed largely of TTL air and not lower tropospheric/boundary layer air. They imposed two different types of passive tracers (initial height scalar and initial water vapour mixing ratio scalar at each grid point) to form a smooth and continuous distribution in the vertical in order to minimize the numerical artifacts that occur near sharp gradients. And estimate of the parcel origin is then simply given by the perturbation value, indicating the degree of the vertical displacement of air and whether there is mixing between significantly different air masses.

[Hassim, M. E. E. and Lane, T. P.: A model study on the influence of overshooting convection on TTL water vapour, Atmos. Chem. Phys., 10, 9833-9849, https://doi.org/10.5149/acp-10-9833-2010, 2010]

We agree that the tracer employed in this study is too simplistic to find out the sophisticated origin of the air mass. In this study, however the purpose of the tropospheric tracer is to see the mixture of tropospheric air and stratospheric air in the layer above 380 K isentropic altitudes. And this simple set up is able to show the changes in the concentration of tropospheric air. For the sake of clarity, Figure 8 has been improved by removing the wind vectors and changing the unit to percentage, while the main changes of the tropospheric tracer within the convective overshoots are pointed by arrows. During 13:00–23:00 UTC on 6 August, the concentration of tropospheric air increases, e.g. from 0 up to about 50 % around 103°E (Fig. 8a–f).

At the same time, as you pointed out, there is limitation of this simple set up to distinguish i) the numerical diffusion by the sharp gradients, and ii) the origins of air parcels coming from the lower, middle or upper troposphere. For this, additional analyses using further detailed setup (e.g. Hassim and Lane, 2010; Dauhut et al., 2016) is required. This limitation has been discussed in the manuscript.

♣ From Page 16, lines 459

"The simple set up of tropospheric tracer of this study, i.e. tropospheric air below the 380 K isentropic altitude, allows to understand the mixture of tropospheric and stratospheric air parcels in the TTL by vigorous convective overshoots. To estimate the detailed origin i.e. defining the lower, middle, and upper troposphere, of air parcel, further sophisticated analyses (e.g. Mullendore et al., 2005; Hassim and Lane, 2010; Homeyer, 2015; Dauhut et al., 2016) will be required."

♣ Reference list

Homeyer, C. R.: Numerical simulations of extratropical tropopause penetrating convection, J. Geophys. Res. Atmos., 120, 7174–7188. doi: 10.1002/2015JD023356, 2015.

Hassim, M. E. E. and Lane, T. P.: A model study on the influence of overshooting convection on TTL water vapour, Atmos. Chem. Phys., 10, 9833–9849, https://doi.org/10.5149/acp-10-9833-2010, 2010

Mullendore, G. L., Durran, D. R., and Holton, J. R.: Cross-Tropopause tracer transport in midlatitude convection, J. Geophys. Res., 110, D06113, doi:10.1029/2004JD005059, 2005.

♣ Page 29

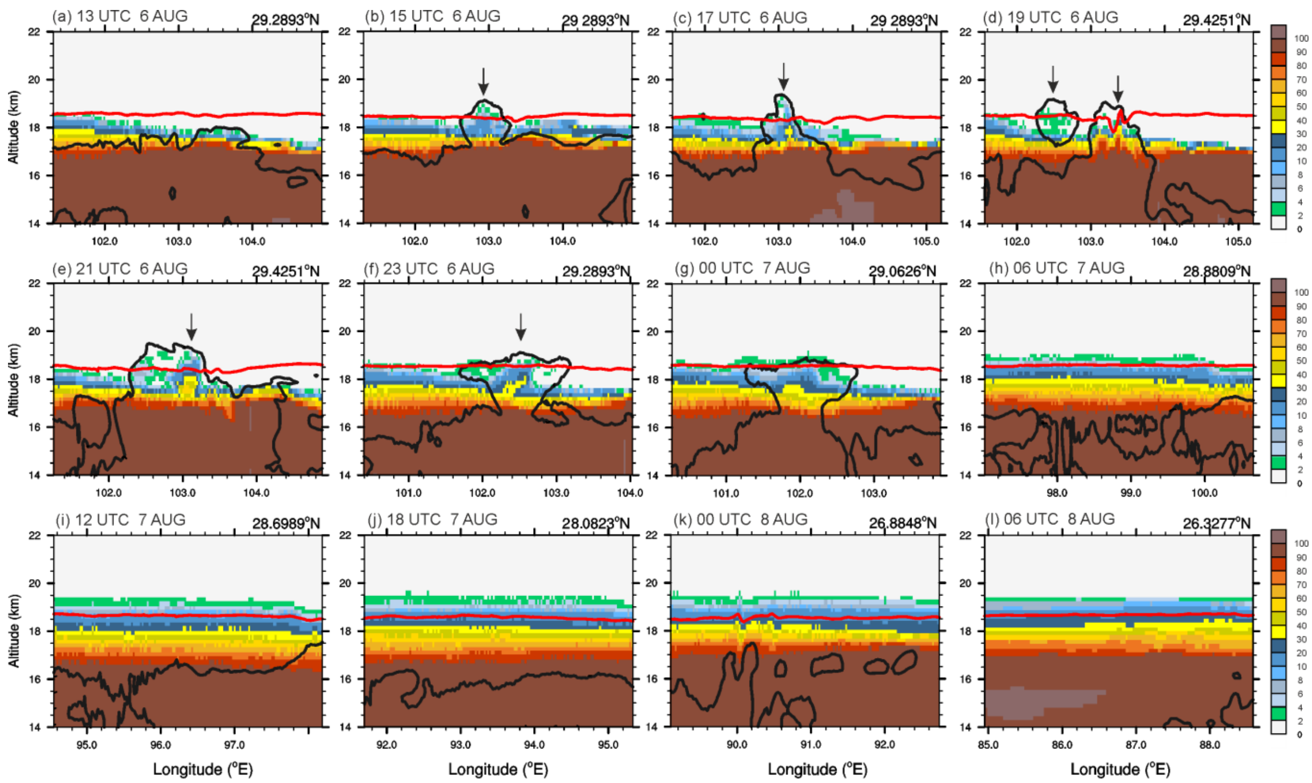


Figure 8. Same as Fig. 7 but for the tracer (%). The isentropic altitude of 410 K is depicted by the red line. The changes of the tropospheric tracer by convective overshoots is marked by downward arrows.

Amount of water vapour injected by convective overshooting

L218–219: Are the authors able to quantify how many overshoots are simulated in domain 4e/4d over the 7 h period reported? A total of 6401 tonnes over a 7 h period implies that approximately 915 tonnes of water were injected every hour, on average. What would be the average amount per overshoot and how does this compare to other studies of single and multiple overshooting cores? Also, can the authors comment whether the convectively-injected amount they derive is sensitive to the model resolution. I suspect that this would be the case since you would get much wider updrafts at 2.5 km resolution compared to a <= 1 km grid spacing.

With hourly output, we are not able to quantify the number of overshoots that developed over the 7h period because of the too low temporal sampling. As showed by Dauhut et al (2018), which focused on an occurrence of the storm Hector the Convector, 46 overshoots developed during one hour of active very deep convection, among which 19 reached the stratosphere, including 12 that hydrated it. Their life time can be as short as 15 min. Instead, we can compare the rate of water injection into the stratosphere with this previous study. With a total of 6401 tonnes over 7 hours, the average rate of 915 tonnes/h is comparable to the Hector injection rate on 30/11/2005 ~ 925 tonnes/h, given the 2776 tonnes injected during a period that lasts ~3h between the start of the increase (~14:00) and the final value (~17:00) in Fig. 4 of Dauhut et al. (2015).

As you suggested, the injected water vapour amount has been re-calculated on isentropic levels of 380–530 K, instead of 17.8–22 km altitudes. We have subtracted the total injected amount of water vapour just before the overshooting, from the amount collected just after the overshooting development over the same domain size. We conclude that during the overshooting period of 7 hours, the total hydration amount of 6088 t are collected having the hourly rate of 869 t.

As you mentioned, it is true that the amount of water vapour is sensitive to the horizontal grid spacing of simulation. For instance, Dauhut et al. (2015) estimated the injected moisture (2776 tonnes) by the Hector the Convector occurring during 1 hour and 40 min, using the simulation results with a grid spacing of 200 m. Through a series of simulations, they showed the impact of horizontal grid spacing to the net hydration amount. For comparison, we keep in mind the different grid spacing and convection duration between the target systems. This has been mentioned in the manuscript.

♣ Page 8, lines 224–228

"[…] The convective overshoots start to be seen from 14:00 UTC on 6 August over the Sichuan basin (Fig. 4e), and they overshoots develop in this region until 21:00 UTC. During the period between 14:00 and 21:00 UTC, the developing overshoots collectively inject a large water vapour hourly budget of 869 t above the CPT (as the result of integrating the water vapour content between two isentropic altitudes of 380 and 530 K)."

♣ Page 15, lines 407–409

"[…] Between 15:00 and 21:00 UTC, the overshooting clouds collectively hydrate the lower stratosphere resulting in the total amount of water vapour of 6088 t."

♣ Page 16, lines 458–459

"[…] In addition, note that the amount of injected moisture is sensitive to the grid spacing of simulation and the convection duration of target system."

I also think that it is important to state in the text that the direct injection of water mass by convective overshoots occurs mainly in the form of ice, as the air within the overshooting of the ice-laden air mixed with the entrained stratospheric air during the collapse of the overshooting top. The warm, subs-saturated stratospheric air causes the ice to rapidly sublimate into vapour at the top of the overshoot, moistening the layer. In lieu of the new higher parcel temperature (due to mixing), the enriched vapour layer then remains at this higher isentropic level after the overshoot collapses. The conditions and timescale at which this process occurs has been investigated by the second author in his 2018 paper and should be highlighted when describing Fig. 6 and 7 later, and in section 4.2.1.

Right. To state above, the following changes have been made.

♣ From Page 9, lines 253

"[…] At 17:00 UTC even higher cloud top is apparent at ~19.5 km altitude (Fig. 6c), a large amount of water vapour (≥ 18 ppmv) rises to ~20 km, around 103°E, and a large ice content (≥ 120 eq. ppmv) stays below 18 km altitude (Fig. 7c). The large amount of water is directly injected by convective overshoots mainly in the form of ice, as the air within the overshooting of the ice-laden air mixes with the entrained stratospheric air during the collapse of the overshooting top. The warm, sub-saturated stratospheric air causes the ice to rapidly sublimate into vapour at the top of the overshoot, moistening the layer. It is worth noting the water injected by the convective overshoots at 15:00 UTC is still apparent in ML at 17:00 UTC around 102°E with a water vapour mixing ratio above 9 ppmv (Fig. 6c). In a similar way, the convectively-injected large moisture at 17:00 UTC around 103°E (Fig. 6c) is found in ML at 19:00 UTC around 102.5°E with a water vapour mixing ratio larger than 15 ppmv (Fig. 6d)."

♣ Page 11, lines 301–311

"[...] During the development of the convective overshoots between 14:00 and 21:00 UTC on 6 August 2017, the average water vapour mixing ratio increases to 5.7 ppmv in IL (yellow solid line, Fig. 9a), while a large mixing ratio of 6.5 ppmv is seen in ML (blue solid line in Fig. 9a). The ice content reaches more than 200 eq. ppmv in both layers, and even more than 300 eq. ppmv in IL (Fig. 9b). Until 17:00 UTC, the temperature increases in both layers (solid lines in Fig. 9c), indicating the mixing with the warmer stratospheric air. Because of this entrained stratospheric air, RH_{ice} decreases largely below 60 % in ML (blue line with symbols in Fig. 9c), and down to 90 % in IL (yellow line with symbols). Due to the mixing with entrained warmer stratospheric air, the enriched vapour layer then remains at this higher isentropic level after the overshoot collapses. The conditions and timescale of the detailed process trapping the enriched vapour in the TTL was demonstrated by Dauhut et al. (2018). Thanks to a fine temporal resolution of 1 min, they revealed that this process occurs shortly within 20 min."

L220–221: Is there a reason why the authors simply integrated the water vapour and not the water vapour anomaly (relative to the initial profile) between the CPT (17.8 km) and 22 km? Wouldn't this result in an overestimation? I would also contend that the net hydration analysis is better done on isentropic levels since, in the absence of diabatic processes, air parcels would remain and travel along a given isentrope determined by their resultant potential temperature.

Agreed. To produce accurate amount of integrated water vapour, we have re-calculated it on isentropic levels between 380 and 530 K, which is corresponding to the altitudes between about 17.8 and 22 km. The newly-calculated amount is slightly smaller than the previous one (6088 t instead of 6401 t). Correspondingly the relevant part in the manuscript has been modified as stated in the answer of preceding comment (see page 6 of this answer sheet).

L247, L257, L270: The small tracer concentrations mentioned here and at other locations in the text when discussing the ML and IL are likely to be numerical artifacts rather than from vertical transport.

In the manuscript, the absolute value of tropospheric tracer (no unit), which ranges between 0 and 1 had been used. For the sake of readability, it has been converted to concentration (unit of percent) which ranges between 0 and 100, throughout the manuscript. At the same time, it is true there is implicit numerical diffusion, generated by the WENO fifth order scheme that partly explains the increase in tracer concentrations.

♣ Page 5, lines 142–143

"[...]The transport scheme for momentum variables is the weighted essentially non-oscillatory (WENO) scheme of 5^{th} order (Shu and Osher, 1988) [...]"

L248: Insert the word 'and' between 'UTC' and 'even'.

Corrected.

L268–278: I feel that the content of the sub-section does not really reflect its heading and does not tell me anything about the advection of the hydration patch. Some of the content describing the amount of water vapour and tracer content is better suited in the preceding sub-section, or perhaps better absorbed into Section 4.2.

Agreed. The aim of this sub-section is to describe the amount of water vapour and tropospheric tracer along the trip of the hydration patch toward the south of Kathmandu. To better reflect the contents, the title has been changed to “Evolution of the hydration patch along its pathway”.

♣ Page 10, lines 271

“4.1.2. Evolution of the hydration patch along its pathway”

L283: Do state the extent of the domain/s that you are averaging along the pathway of the hydration patch. Are they the same ones shown in Fig. 4?

Yes, the same domain extent of the hydration patch is used for averaging along the pathway. This tip of information has been included in the manuscript.

♣ Page 6, lines 164–167

“The area of the hydration patch is about 6,000 km^2, but it is reduced by one fourth to about 1,500 km^2 during the initial overshooting phase in the convective region. This domain is used to calculate the average values of water vapour, ice content, temperature, and relative humidity displayed in Figures 9, 10 and 11.”

Mixing processes affecting the overshoot and the hydration patch

L290: Shouldn’t the figure reference at the end of the sentence be Fig. 9, not Figs. 6 and 7?

You are right. Thank you for pointing this out. The reference has been corrected to Fig. 9.

L293: Replace the word ‘even’ with ‘and’.

Corrected.

L297–298: The difference between the yellow and green lines in Fig. 10a are likely dominated by numerical diffusion in the model acting to smooth the sharp gradients.

Between the yellow and green lines, i.e. during 13:00–21:00 UTC, the active mixing of the convective overshoots changes the vertical profiles of tropospheric tracer, for instance more than 10% of tropospheric air increase at the altitude of 17 km (Fig. 10a), and a large increase of relative humidity between 16.5 and 18.5 km. Of course, there is a contribution of numerical diffusion, but the main changes are induced by the convective hydration.

L300: increases of 5

Corrected.

L303 onwards: In discussing Fig. 11, are the authors confident that they are sampling the same tracked air parcels at 12 UTC 7 Aug (11c) and at 06 UTC 8 Aug (11d), as those sampled initially on 21 UTC 6 Aug (11b)?

The domain of the hydration patch is considered for the analysis of Figure 11. As the hydration patch travels along its pathway toward west-southwest, the air parcel could be modified by mixing with its environment. This tip of notice has been included in the manuscript.

♣ Page 6, lines 164–167

“The area of the hydration patch is about 6,000 km^2, but it is reduced by one fourth to about 1,500 km^2 during the initial overshooting phase in the convective region. This domain is used to calculate the average values of water vapour, ice content, temperature, and relative humidity displayed in Figures 9, 10, and 11."

L308: Shouldn't 'very small compounds of stratospheric air' be 'very small compounds of tropospheric air' since you are referring to tracer content being less than 0.1.
You are right. It has been corrected correspondingly.

L321: This sentence sounds awkward to me. Consider revising. Also, what could be the cause of the mixing at the later times beyond 00 UTC 7 Aug and the isentropes relax back to equilibrium after the overshooting stops? Also, Fig. 9b suggests that there is still a low concentration of cloud ice in both ML and IL long after the snow and graupel sediment out. The continued presence of cloud ice in ML suggests that the ice may have formed in-situ in response to wave-driven temperature oscillations that locally drive the RH to ice saturation. This would suggest that ice microphysics could be playing a pivotal role in controlling the eventual moisture content since ice nucleation and the subsequent growth process would slowly deplete the layer of water vapour.
It is a reasonable explanation to state better in the text. The sentence has been modified accordingly.

♣ Page 12, lines 335–339
"Meanwhile ice sediment out, still there is a low concentration of cloud ice in both ML and IL, and the water vapour concentration slightly decreases (blue solid line in Fig. 10a). The continued presence of cloud ice in ML suggests that the ice may have formed in-situ in response to wave-driven temperature oscillations that locally drive the RH to ice saturation. The ice microphysics might play a pivotal role in controlling the eventual moisture content since ice nucleation and the subsequent growth process to deplete slowly the ML. […]"

L326: Insert 'is' between 'The' and 'probably'. Again, what domain is the analysis in Fig. 9 performed for?
Corrected.

L333–342: I am not fully convinced that turbulent diffusion is the sole cause of the decrease in water vapour content in ML and IL. For reasons above, vapour-scavenging by ice nucleation and growth within ML and IL might also explain the reduction in water vapour amount. I would recommend plotting Fig. 10b-d as anomalies with respect to the background initial profile at the various locations along the trajectory. This would allow the authors to properly discern whether net moistening or dehydration took place at the different levels and allow the dominant processes to be elucidated better. For Fig. 10e, it would be useful to also plot just cloud ice as dashed lines for the stated times.
Agreed. In Figure 10, the profiles (yellow lines) of 13:00 UTC on 6 August, which is a few hours before the overshoot development, represents the initial state. The comparison between this initial state and other three times allow to understand the evolution (hydration or dehydration) of air parcel, especially in ML and IL. To better understand the water vapour scavenging effect by ice nucleation and growth within ML and IL, the ice content (solid lines) and cloud ice (dashed lines) are separately displayed in Figure 11s (previously Figure 10e). The latter shows that IL includes much reduced amount of ice content than the previous time (green to blue solid lines), but still there exists ice content ≥ 1 eq. ppmv and cloud ice ≥ 0.5 eq. ppmv at 12:00 UTC on 7 August (blue dashed line). Meanwhile, the turbulent kinetic energy (TKE) largely increases from 0.1 to 0.3 $m^2 s^{-2}$ in both ML and IL (Fig. 9). Thus we conclude that the turbulent diffusion is the main source for dehydrating ML

and IL, but it is not the sole cause. The vapour-scavenging effect plays a role in decreasing the water vapour amount. The manuscript has been improved by including this point.

♣ Page 13, lines 354–358

"The two layers become colder by ~3°C (green to blue lines in Fig. 11b), and dehydrated compared to the initial state of 13:00 UTC on 6 August (yellow line in Fig. 11d, e). It includes much reduced amount of ice content (green to blue solid lines in Fig. 11e), but still there exist ice content ≥ 1 eq. ppmv and cloud ice ≥ 0.5 eq. ppmv at 12:00 UTC on 7 August (blue dashed line, Fig. 11e)."

♣ Page 13, lines 364–365

"Also, the vapour-scavenging effect by ice nucleation and growth within IL contributes to reduce the water vapour deriving the dehydration."

♣ Page 32

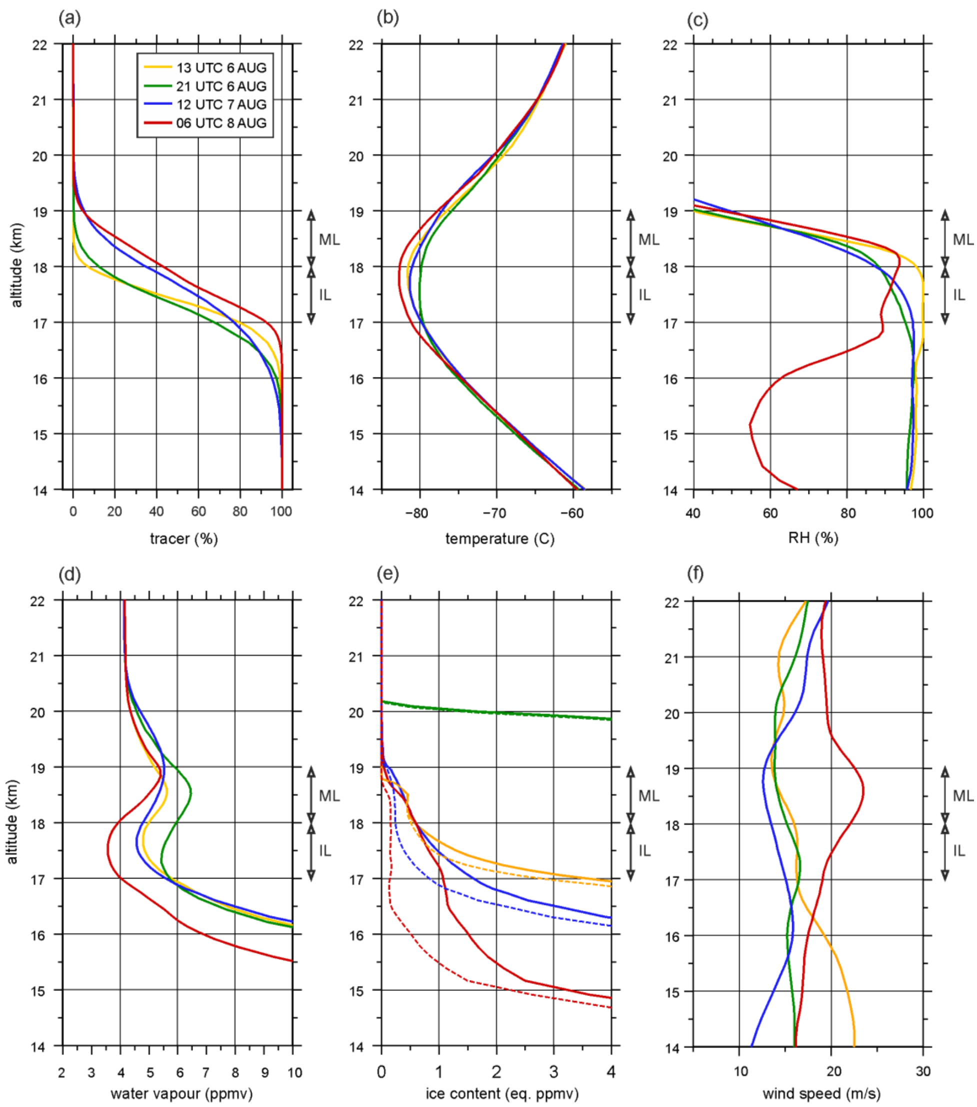


Figure 11. Vertical profiles of (a) tracer (%), (b) temperature (°C), (c) relative humidity (%), mixing ratios of (d) water vapour (ppmv), (e) ice content (eq. ppmv), and (f) wind speed (m s^{-1}) across the hydration patch along the trajectory at 13:00 UTC (yellow line), 21:00 UTC (green line) on 6 August, 12:00 UTC on 7 August (blue line), and 06:00 UTC (red

line) on 8 August 2017. The layers of ML and IL are marked by arrows. In (e), the ice content are depicted by solid lines, while the cloud ice are shown by dashed lines.

L350: Should the figure reference be '10d' and not '11d'?
It is. It has been corrected, correspondingly.

L351: At which location along the trajectory of the hydration patch is cold tropospheric air being entrained to reduce the ML and IL temperature? It could just be that the patch encountered colder background temperatures on 06 UTC 8 Aug.
Agreed. The possibilities of both the entrainment of cold tropospheric air and colder background air have been stated in the manuscript.

♣ Page 13, line 372−373
"The entrained cold tropospheric air (and/or colder background air) and the hydrostatic adjustment decrease the temperature in ML and IL (Fig.10b)."

L361: '…decreases from 9.6 to below 6.2 ppmv…'
Corrected.

L363–364: I would argue that the reduction in ice content is largely due to sedimentation and not sublimation due to mixing as the water vapour content is also steadily decreasing with time. Only a fraction of the ice mass transported into the TTL will be sublimated before most of the ice sediments out.
Agreed. The relevant sentence has been modified.

♣ Page 14, lines 384−385
"The reduced ice content in ML and IL might be induced by sedimentation thanks to the mixing with the dry tropospheric air (RH_{ice} ~50−70 %) […]"

L365: This statement is highly speculative without showing any profiles of TKE. By 012 UTC 7 Aug, the isentropes are back to a relaxed position and not perturbed further by overshoots.
For the sake of clarity, the vertical cross-sections of TKE from 13:00 UTC on 6 August to 06:00 UTC on 8 August have been joined as Figure 9 in the manuscript and further details about the TKE structure have been included.

♣ Page 10, line 269−270
"[…] During 17:00−21:00 UTC (Fig. 9c−e), the large turbulent kinetic energy (TKE) of 0.2−0.9 $m^2\ s^{-2}$ is apparent in a limited area of cloud top (~103°E)."

♣ Page 10, line 276−277
"[…] Within the anvil cloud, still large TKE of 0.2−0.9 $m^2\ s^{-2}$ is seen (Fig. 9f, g)."

♣ Page 10, line 283–285

"[…] The air mass with high tropospheric tracer concentration of 2–40 % consistently exists in ML and IL from 00:00 to 06:00 UTC on 8 August 2017 (Fig. 8k–l), while the TKE of 0.2–0.9 m^2 s^{-2} exists in wide area between the altitudes of 16 and 18 km (Fig. 9k–l)."

♣ Page 13, line 360–361

"[…] Moreover, the turbulent kinetic energy (TKE) increases from 0.1–0.3 m^2 s^{-2} at 21:00 UTC to 0.2–0.9 m^2 s^{-2} at 12:00 UTC in ML and IL (~~not shown~~Fig. 9e, i)."

♣ Page 14, line 391–392

"[…] The air mass in ML and IL has large TKE values of 0.5 m^2 s^{-2} (~~not shown~~Fig. 9l)."

♣ Page 30

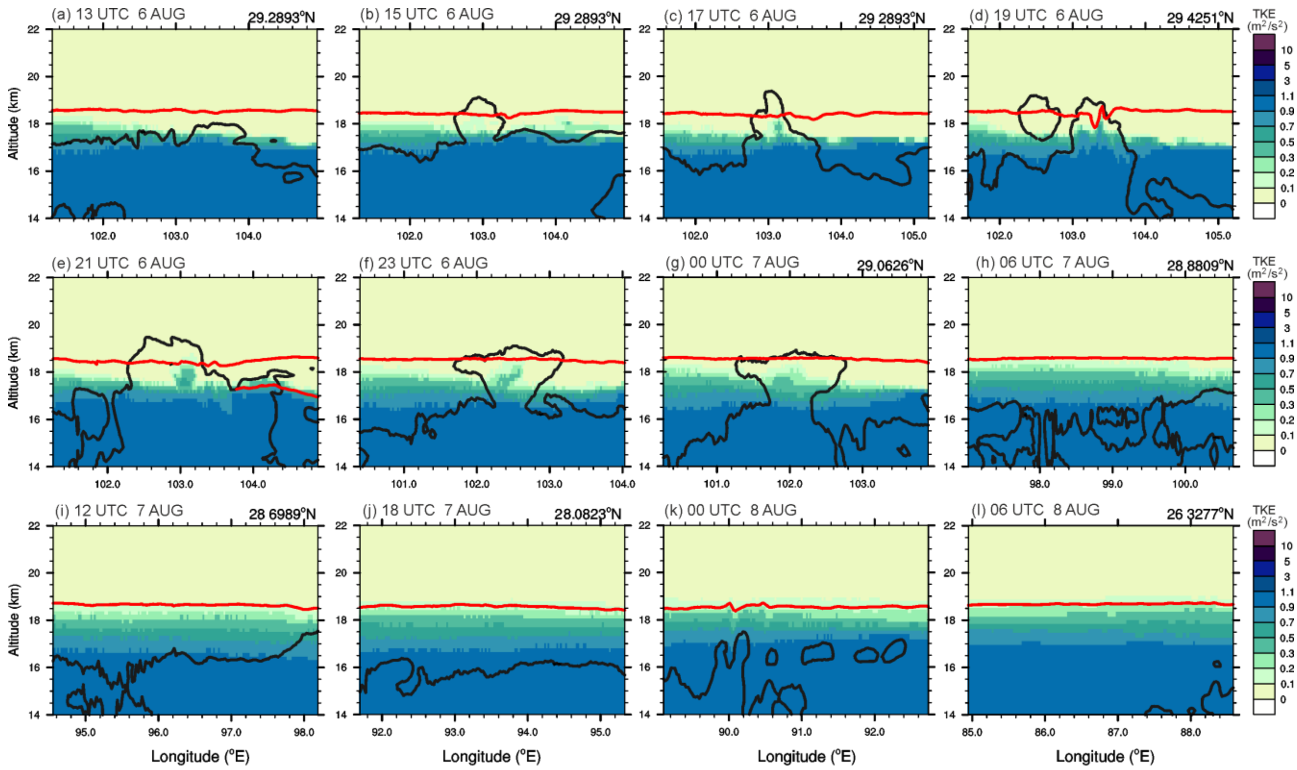


Figure 9. Same as Fig. 6 but for the TKE. The isentropic altitude of 410 K is depicted by the red line.

L366: '…in excess of…'

Corrected.

L368: What do you mean by 'wind shear layer'? I also do not see a straight upward profile in temperature on 06 UTC 8 Aug.

Figure 2e shows a sharp increase of wind speed in the bottom half of ML (18–18.5 km), where the temperature (Fig. 2b) is nearly constant (about –80°C) instead of a sharp increase. In this layer, TKE value of 0.5 m^2 s^{-2} (Fig. 8l) and large tropospheric air concentration of 20–30% (Fig. 9l) suggest the gradual mixing of air parcel by vertical wind shear. For the sake of clarity, the relevant sentence has been modified.

♣ Page 14, line 389–391

"[...]Also, this wind shear layer with a large gradient of wind speed (25–35 m s^{-1}) locates below and above the CPT (Fig. 2c, 2e), thus it results in the strait upward temperature profile with the constant value about –80°C at 06:00 UTC on 8 August as seen in Fig. 10b (red line)."

Additional Comments:

L22: Change 'still remains' to 'remained'. Remove 'ASL' as the word altitude implies that it is above sea level.

Corrected.

L23–24: The two sentences here sound awkward in their construction. Suggest authors re-word them for clarity and flow of meaning.

Corrected.

♣ Page 1, line 24–25

"[...] At the same time, a great part of the hydrometeors falls shortly, and ~~the rest sublimates. Meanwhile ice sediments out,~~ the water vapour concentration in ML and IL decreases due to turbulent diffusion by mixing with the tropospheric air and in-situ ice microphysics."

L24–25: There are issues with the way the tracer is implemented for this statement to be robust and valid, without at least accounting for the role of ice microphysics, specifically in-situ ice nucleation and growth, which would deplete the water vapour content.

Agreed. The pivotal role of ice microphysics has been stated in the manuscript.

♣ Page 1, line 24–25

"[...] the water vapour concentration in ML and IL decreases due to turbulent diffusion by mixing with the tropospheric air and in-situ ice microphysics."

L35: '...and the Middle East, and is located...'

Corrected.

L43: '...high at about 4.2ppmv...'

Corrected.

L56: '...the most energetic air parcels form...'

Corrected.

Fig. 2: It would be useful for the reader if the background water vapour content value is shown by a vertical reference line in 2(a).

Thank you for the nice suggestion. In this study, however the main approach is that the water vapour amount at ML is relatively larger than other layers above tropopause. Thus we prefer to keep the figure as it is.

Fig. 3: Label (c) and (d) when captioning the 'ice content (eq. ppmv)' and 'water vapour (ppmv)', respectively.

Corrected.

Fig. 5: I suggest that the authors draw lines on the various panels to denote where the Fig. 6 cross-sections for the various times are taken from. Do state in the caption what the white arrows are meant to show.

Corrected.

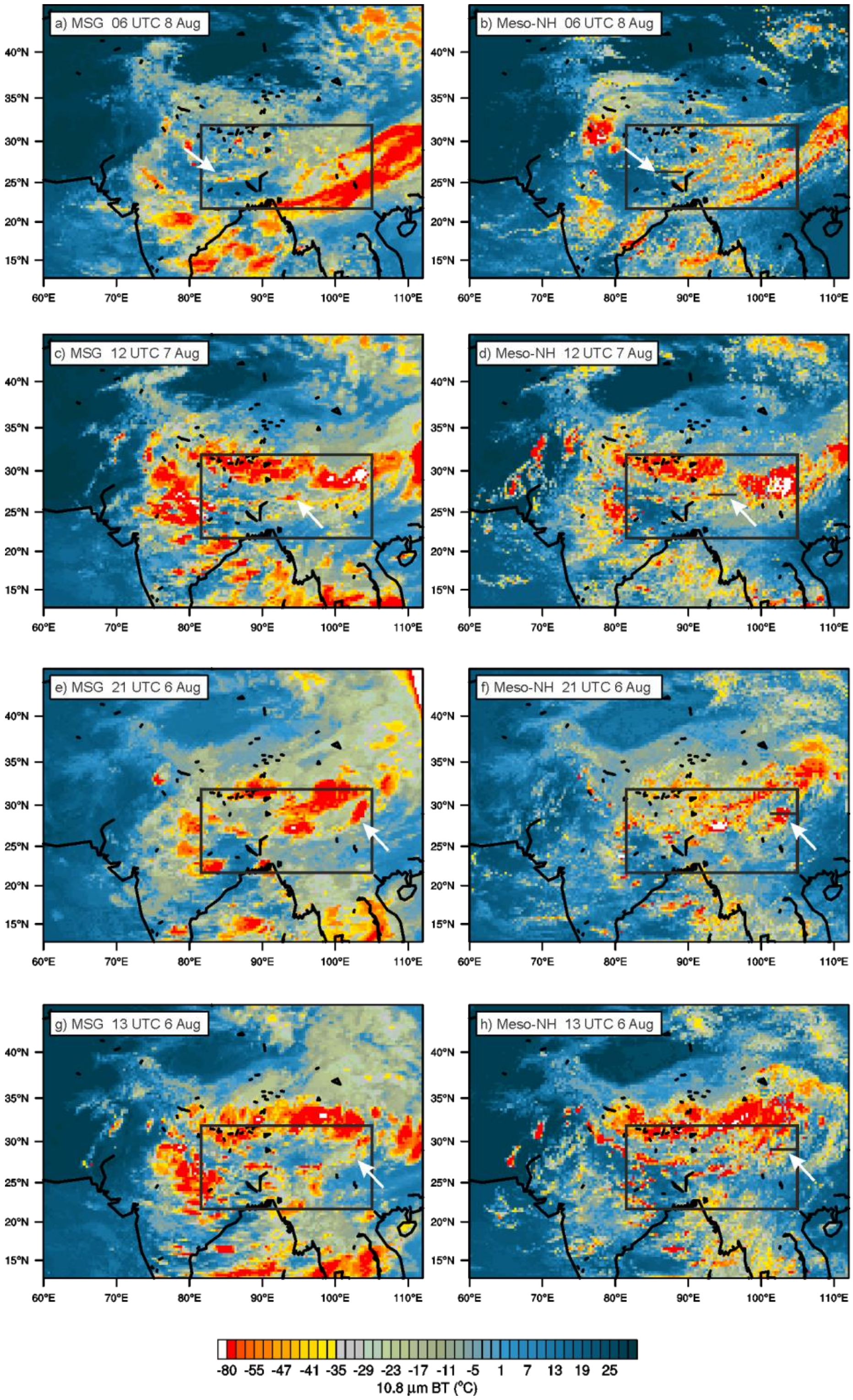


Figure 5. BT 10.8 µm obtained from SEVIRI/MSG (left) and Meso-NH (right) at (a)−(b) 06:00 UTC on 8 August, (c)−(d) 12:00 UTC on 7 August, (e)−(f) 21:00 UTC, and (f)−(h) 13:00 UTC on 6 August 2017. The domain used in Figure 4 is marked by a box in each panel, while the location of vertical cross-sections used in Figures 6−9 is marked by a black solid line in the right panels. The location of hydration patch is depicted by the white arrows.

Fig. 5: What is the small inset box in Fig. 5g and 5h?

The box has been replaced by a solid line to depict the location of the vertical-cross sections shown in Figures 6–9.

Fig. 6: It is hard to see the cloud boundaries in the figure as they are the same colour as the vector winds, which are not discussed at all. I suggest you plot the cloud boundaries as a thick white contour to stand out in Fig. 6. Also, do state in the captions that the arrows plotted denote vector winds and discuss them in text; otherwise remove.

For the sake of readability, Figure 6 has been revised and the wind has been stated in the manuscript.

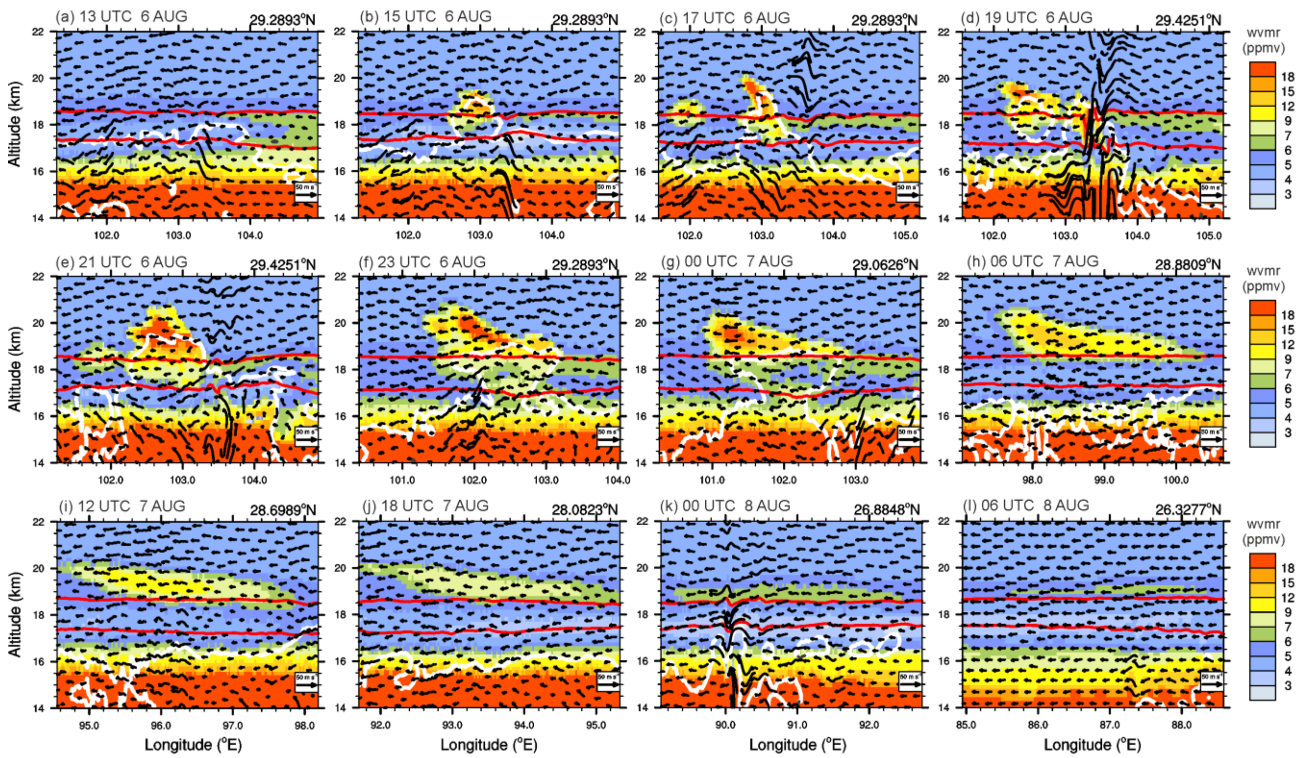
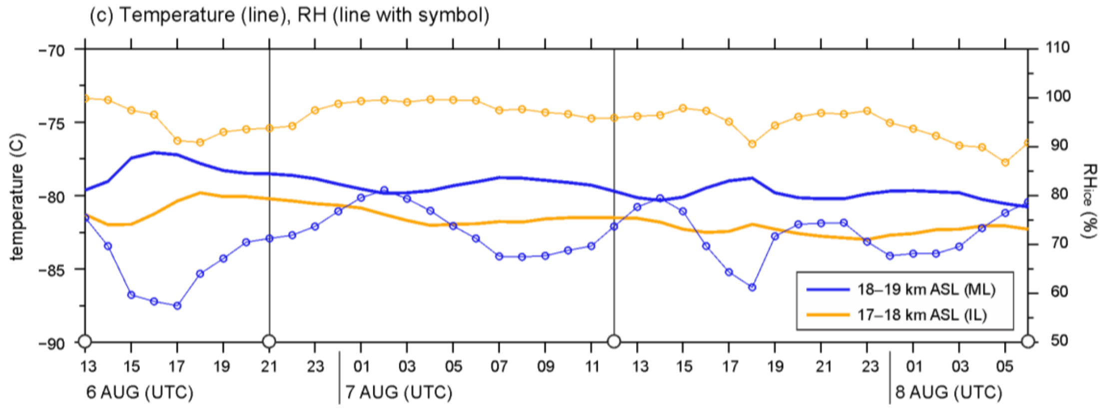


Figure 6. Vertical cross-sections of water vapour mixing ratio (shading) and wind (vectors) (a) 13:00 UTC, (b) 15:00 UTC, (c) 17:00 UTC, (d) 19:00 UTC, (e) 21:00 UTC, (f) 23:00 UTC on 6 August 2017, (g) 00:00 UTC, (h) 06:00 UTC, (i) 12:00 UTC, (j) 18:00 UTC on 7 August 2017, and (k) 00:00 UTC and (l) 06:00 UTC on 8 August 2017. The isentropic altitudes of 380 and 410 K are depicted by the red lines. The latitude (°N) of west-east oriented cross-section line is indicated at the upper right of each panel. The cloud boundary (mixing ratio of ice content of 10 mg kg^{-1}) is contoured by the white solid line.

Fig. 9c: Change ‘temeperature’ to ‘temperature’ for y-axis label.

Corrected.



L373: Change ‘pathways’ to ‘pathway’.

Corrected.

L375: Change ‘convective overshoot’ to ‘overshooting convection’.

Corrected.

Fig. 12 is missing critical components related to ice microphysics such as ice nucleation, growth and sedimentation that ultimately govern TTL humidity through the balance between moistening (from sublimation) and depletion (through scavenging).

Agreed. Figure 12 has been revised by mentioning the ice microphysics.

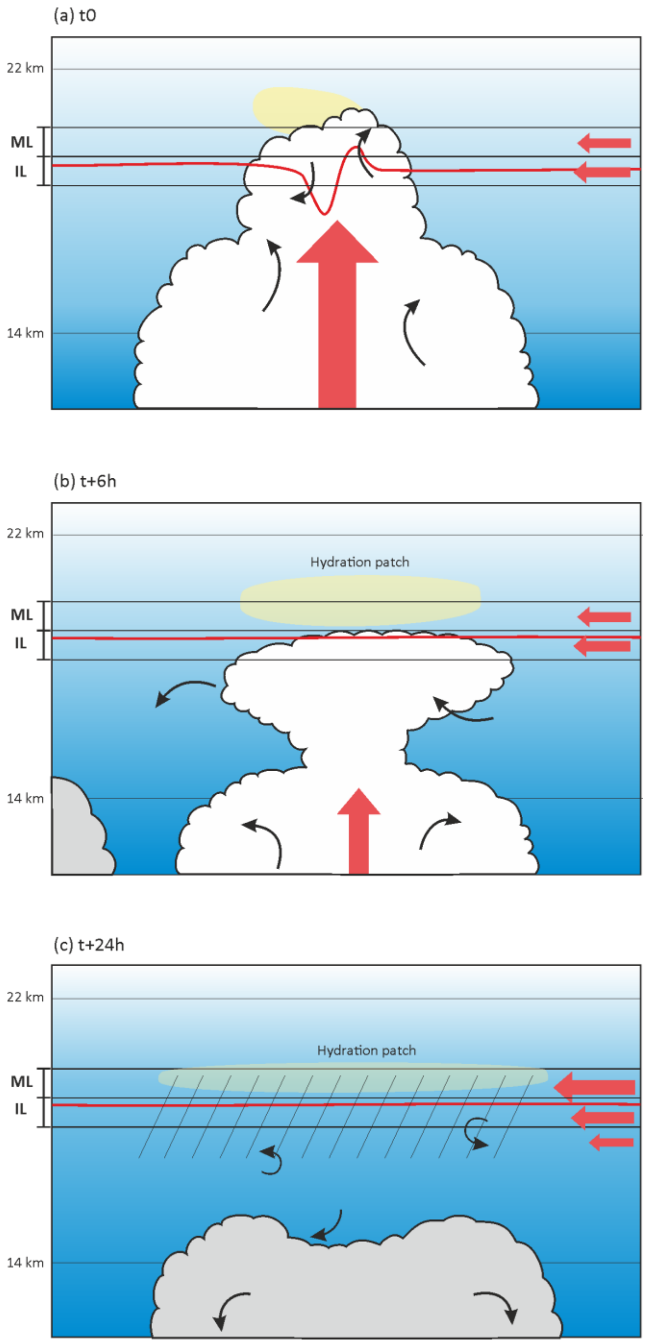


Figure 13. Schematic illustration summarising the hydration process in the TTL during flight #7 of the StratoClim 2017 field campaign. (a) Mixing of the overshoots with the stratospheric air, (b) and (c) turbulent mixing of the hydration patch with the tropospheric air by vertical wind shear. The bottom and top of the TTL, 14 and 22 km, and the moist layer (ML) and ice layer (IL) are represented by the black solid line, and the 410 K isentropic altitude is represented by the red solid line. The main force in the TTL is marked by bold red arrows, while the turbulent eddies in/around the developed and weakened overshoots are described by black arrows. The overreaching water vapour above the cloud top level is indicated by a yellow ellipsoid in (a). The hydration patch is yellow-encapsulated in (a) and (b), and the layer of dehydration by turbulent diffusion and ice microphysics is hatched in (c). The blue shades illustrate the concentration of tropospheric air, showing the increased tropospheric air in the TTL by the turbulent mixing in (b) and (c).

L407–408: From a microphysical perspective, how does turbulent mixing cause water vapour to be partly deposited?
For the sake of clarity, the sentence has been revised.

♣ Page 15, line 427–430
"[…] A part of the water vapour has been lost due to ice formation and sedimentation and the turbulent diffusion in both vertical and the horizontal direction (black arrows in Fig. 13b). The ice microphysics might play a pivotal role in controlling the eventual moisture content since ice nucleation and the subsequent growth process would slowly deplete the water vapour."

L413–414: I think this statement incorrect since average water vapour content is decreasing as shown by Fig. 9a and Fig. 10d, and not increasing.
Corrected.

♣ Page 16, line 435–436
"[…] Due to mixing with the dry tropospheric air, the remaining water vapour in ML gradually diffused in horizontal and vertical direction (ellipse)."

L421–422: The sentence here is poorly constructed and its meaning is hard to understand.
Corrected.

♣ Page 16, line 441–443
"[…] In addition, after the strong updraughts of overshooting convection, the remained horizontal divergence in the lower stratosphere might let the tropospheric air continues to ascend."

L425–427: The statement here is a little far-fetched. After re-reading through section 4 again, the text lacks adequate and systematic discussion on the relative roles of transport, mixing, and ice microphysics to determine which process dominates (c.f. Hassim and Lane, 2010).
Agreed. Further discussion has been stated in the manuscript.

♣ From Page 16, line 459
"[…] The simple set up of tropospheric tracer of this study, i.e. tropospheric air below the 380 K isentropic altitude, allows to understand the mixture of tropospheric and stratospheric air parcels in the TTL by vigorous convective overshoots. To estimate the detailed origin i.e. defining the lower, middle, and upper troposphere, of air parcel, further sophisticated analyses using different passive tracers (e.g. Mullendore et al., 2005; Hassim and Lane, 2010; Homeyer, 2015; Dauhut et al., 2018) will be required."

L433–434: I think the value quoted here is an overestimation due to the way it is calculated.
Agreed. For the comparison, averaged value of injected moisture for 7 hours of convection activity has been considered.

♣ Page 16, line 454–462
"[…]From the hourly averaged budget of 869 t, we can also confirm that the local impact of overshoots developed during the Asian summer monsoon is stronger than the one over tropical Africa (300–500 t

according to Liu et al., 2010) and is weaker than Hector the Convector over the Tiwi Islands (2776 t according to Dauhut et al., 2015). Because of a large variety in the lifetime and horizontal scale of overshoots, an accumulation of more event-scale analyses is important. In addition, note that the amount of injected moisture is sensitive to the grid spacing of simulation deriving larger amount with larger grid spacing. The simple set up of tropospheric tracer of this study, i.e. tropospheric air below the 380 K isentropic altitude, allows to understand the mixture of tropospheric and stratospheric air parcels in the TTL by vigorous convective overshoots."

Convective hydration in the tropical tropopause layer during the StratoClim aircraft campaign: Pathway of an observed hydration patch

By K. O. Lee et al.

Reply to the referees' comments

In the following, the comments made by the referees appear in black, while our replies are in red, and the proposed modified text in the typescript is in blue.

Referee #3 comments

General Comments

This article investigates an observed hydration patch in the area of the Asian Monsoon observed by the StratoClim aircraft campaign. The Meso-NH model is run over several days and accurately simulates the hydration patch and the proceeding convection. The simulation demonstrates the hydration patch can be attributed to convective influence from the days prior to the observation. I think this is an interesting case and the tracking back in time of the hydration patch to see how the atmosphere responds to the convective influence is compelling. However, this article also attempts to describe in more detail the physical and dynamical processes that explain the evolution of the atmospheric environment. I found much of this text to be poorly supported. The specific statements that need more support are listed below. Or the authors could choose to remove some of these statements because they can't be investigated with the current model (or time does not permit investigation). In that case, the authors can submit a revised article that is a much more concise case study of an interesting simulated hydration event.

Additionally, the authors fail to reference several articles on mid-latitude hydration and/or convective transport events that seem relevant for this study. A non-exhaustive list of these articles are included in the comments below.

We appreciate the time and effort you put in this review as well your mindful comments on our paper. We have worked hard to state clearly the processes and to list up-to-date reference articles on mid-latitude hydration and convective transport events. Replies to each comment are listed below.

Comments on Process Statements:

1. The separation between the troposphere and stratosphere is identified as the 380 K level. This is a reasonable definition in the mean, but is an oversimplified definition at convection-allowing scales. I think this study clearly shows deep injection of water vapor by convection, but there should be some discussion of the difficulty of defining a tropopause in convective environment. For example, see:

Maddox, E.M. and G.L. Mullendor, 2018: Determination of Best Tropopause Definition for Convective Transport Studies. J. Atmos. Sci., 75, 3433–3446, https://doi.org/10.1175/JAS-D-18-0032.1

Agreed. There exist several tropopause definitions in various literature (e.g. Maddox and Mullendore, 2018), considering temperature lapse rate, potential vorticity, static stability, and tracer chemicals. As you mentioned, it is true that there is a difficulty of defining a tropopause in convective environment. This has been discussed in the manuscript as below:

♣ From Page 6, lines 171

"[…] There exist several tropopause definitions, considering temperature lapse rate, potential vorticity, and static stability (WMO, 1957; Maddox and Mullendore, 2018). In this study, the overshoots are defined as convective cloud tops that reach the lowermost stratosphere above 380 K level. This simple definition is sufficient enough to study the impact of convective hydration on the TTL as it quickly returns to its undisturbed state (Dauhut et al., 2018)."

2. Using the tropopause definition above, a tropospheric tracer is defined to track mixing between the troposphere and stratosphere. There is the issue discussed above of an oversimplified tropopause definition. But more importantly, this is an odd approach to highlighting moistening from the troposphere. I expect the moisture content of the upper troposphere in this region is much lower than the moisture content of the lower troposphere. The approach used here has no way to distinguish between mixing of lower tropospheric (as transported by deep convection) or upper tropospheric air. Additionally, because the tropospheric air being tracked is right at tropopause level, a lot of the observed mixing may occur due to numerical diffusion, which tends to be stronger than true atmospheric diffusion. (And even if the numerical diffusion is physical, may track mixing of air parcels that are not very different in terms of water vapor content). This issue can be seen in Figure 8 with the strong gradient that forms at all locations over time, which just looks like diffusion. It would be instructive to show what the tropospheric tracers looks like away from convective events to assess what portion of the vertical mixing is convectively enhanced and what portion is just diffusion. Figure 11 is not compelling. Finally I don't know of any tropospheric chemical tracer that looks like that (Figure 8) across the tropopause.
Note: I do agree that the mixing is enhanced around the time of convection, but it's not clear if the mixing is of significantly different air masses, or just enhancing the diffusive processes in the vicinity of convection. Again, this problem is due to that fact that you don't know where in the troposphere this air is from. Many articles have used tracers to study deep convective transport, but are able to better distinguish source. For example:

Homeyer, C.R. (2015), Numerical simulations of extratropical tropopause–penetrating convection: Sensitivities to grid resolution. J. Geophys. Res. Atmos., 120, 7174–7188. Doi: 10.1002/2015JD023356
Mullendor, G.L., D.R. Durran, and J.R. Holton (2005), Cross-Tropopause tracer transport in midlatitude convection, J. Geophys. Res., 110, D06113, doi:10.1029/2004JD005059

We agree that the tracer employed in this study is simplistic to find out the sophisticated origin of the air mass. In this study, however the purpose of the tropospheric tracer is to see the mixture of tropospheric air and stratospheric air in the layer above 380 K isentropic altitudes. And this simple set up is able to show the changes of the concentration of tropospheric air. For the sake of clarity, Figure 8 has been improved by removing the wind vectors and changing the unit to percentage ranging from 0 to 100, while the main changes of the tropospheric tracer within the convective overshoots are pointed by arrows. During 13:00–23:00 UTC on 6 August, the concentration of tropospheric air increases, e.g. from 0 up to about 50 % around 103°E (Fig. 8a–f).

At the same time, as you pointed out, there is limitation of this simple set up to distinguish i) the numerical diffusion by the sharp gradients, and ii) the origins of air parcels coming from lower, middle or upper tropospheric air. For this, additional analyses using further setup (e.g. Mullendore et al., 2005; Hassim and Lane, 2010; Homeyer, 2015; Dauhut et al., 2016) is required. This limitation has been discussed in the manuscript.

♣ From Page 16, lines 459
"The simple set up of tropospheric tracer of this study, i.e. tropospheric air below the 380 K isentropic altitude, allows to understand the mixture of tropospheric and stratospheric air parcels in the TTL by vigorous convective overshoots. To estimate the detailed origin i.e. defining the lower, middle, and upper troposphere, of air parcel, further sophisticated analyses (e.g. Mullendore et al., 2005; Hassim and Lane, 2010; Homeyer, 2015; Dauhut et al., 2016) will be required."

♣ Reference list

Homeyer, C. R.: Numerical simulations of extratropical tropopause penetrating convection, J. Geophys. Res. Atmos., 120, 7174–7188. doi: 10.1002/2015JD023356, 2015.

Hassim, M. E. E. and Lane, T. P.: A model study on the influence of overshooting convection on TTL water vapour, Atmos. Chem. Phys., 10, 9833–9849, https://doi.org/10.5149/acp-10-9833-2010, 2010

Mullendore, G. L., Durran, D. R., and Holton, J. R.: Cross-Tropopause tracer transport in midlatitude convection, J. Geophys. Res., 110, D06113, doi:10.1029/2004JD005059, 2005.

♣ Page 29

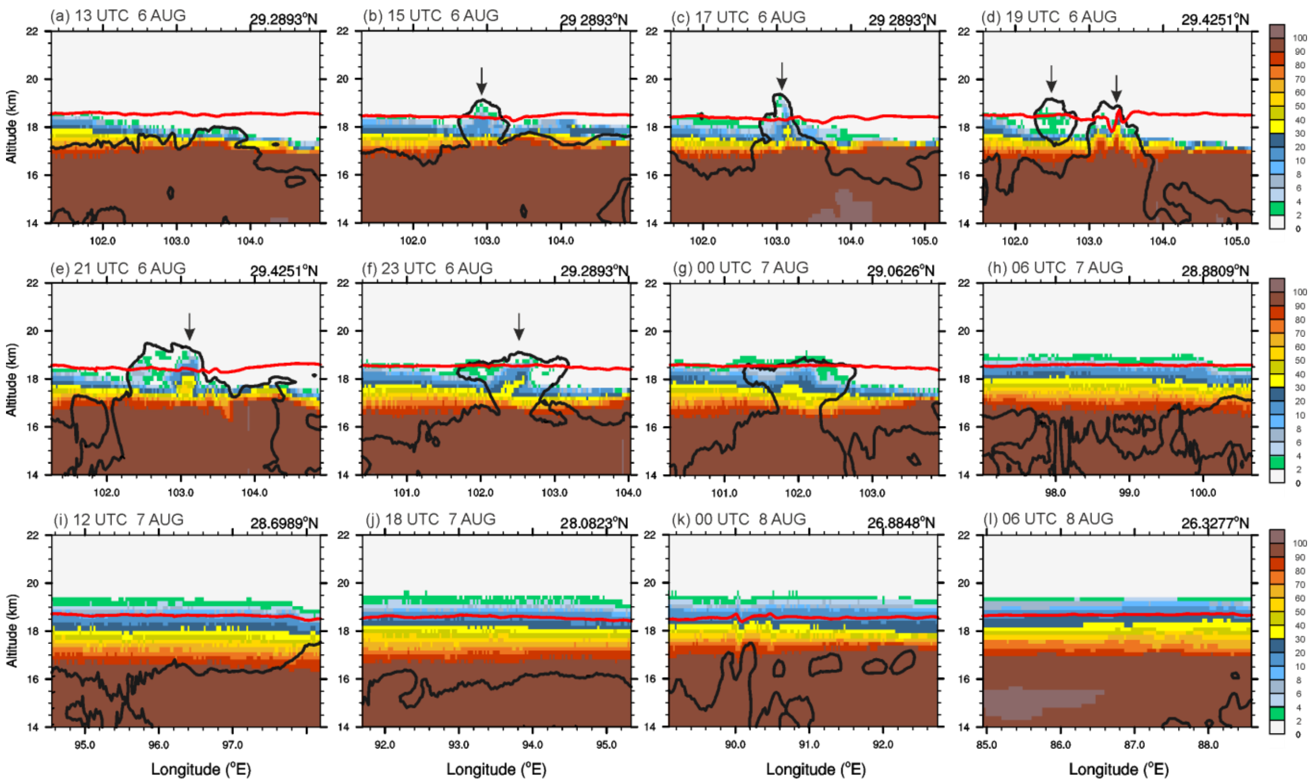


Figure 8. Same as Fig. 7 but for the tracer (%). The isentropic altitude of 410 K is depicted by the red line. The main changes of the tropospheric tracer by convective overshoots is marked by downward arrows.

3. The definition of ML and IL is based on height ranges. Line 294 states that "the temperature increases in both layers, indicating the mixing with the warmer stratospheric air". As shown in Maddox and Mullendore (2018; reference above), during the convective event, the tropopause cannot be reliably defined, but we at least know that the tropopause surface is pushed upward during the event. "Mixing with stratospheric air" doesn't make sense here. If you are showing the influence of overshoots only, which are colder than the surrounding air, the layer temperature will go down. You may instead be seeing the tropospheric column heating occurring due to the convection (e.g. see comment in Maddox and Mullendore, p. 3438). Or this may be due to local heating due to ice particle formation.

It is true that the strong updraughts of overshooting convective system perturb the tropopause layer, injecting a large amount of tropospheric moisture across the tropopause. During the collapse of the overshooting top, the stratospheric dry and warm air can flow in. The conditions and timescale of the detailed process trapping the enriched vapour in the TTL was demonstrated in Dauhut et al. (2018). Thanks to a fine temporal resolution of 1 min, they reveal that this process occurs shortly within 20 min. The warm, sub-saturated stratospheric air causes the ice to rapidly sublimate into water vapour at the top of the overshoot, moistening the layer. It is thus that both intrusion of stratospheric air by the overshooting convection and activated ice microphysics derives the increase of temperature in ML and IL. This discussion has been stated in the manuscript.

♣ From Page 9, lines 253

"At 17:00 UTC even higher cloud top is apparent at ~19.5 km altitude (Fig. 6c), a large amount of water vapour (≥ 18 ppmv) rises to ~20 km, around 103°E, and a large ice content (≥ 120 eq. ppmv) stays below 18 km altitude (Fig. 7c). The large amount of water is directly injected by convective overshoots mainly in the form of ice, as the air within the overshooting of the ice-laden air with the entrained stratospheric air during the collapse of the overshooting top. The warm, sub-saturated stratospheric air causes the ice to rapidly sublimate into water vapour at the top of the overshoot, moistening the layer. It is worth noting the water injected by the convective overshoots at 15:00 UTC is still apparent in ML at 17:00 UTC around 102°E with a water vapour mixing ratio above 9 ppmv (Fig. 6c). In a similar way, the convectively-injected large moisture at 17:00 UTC around 103°E (Fig. 6c) is found in ML at 19:00 UTC around 102.5°E with a water vapour mixing ratio larger than 15 ppmv (Fig. 6d)."

♣ Page 11, lines 301–311

"[…] During the development of the convective overshoots between 14:00 and 21:00 UTC on 6 August 2017, the average water vapour mixing ratio increases to 5.7 ppmv in IL (yellow solid line, Fig. 10a), while a large mixing ratio of 6.5 ppmv is seen in ML (blue solid line in Fig. 10a). The ice content reaches more than 200 eq. ppmv in both layers even more than 300 eq. ppmv in IL (Fig. 10b). Until 17:00 UTC, the temperature increases in both layers (solid lines in Fig. 10c), indicating the mixing with the warmer stratospheric air. Because of this entrained stratospheric air, RH_{ice} decreases largely below 60 % in ML (blue line with symbols in Fig. 10c), and down to 90 % in IL (yellow line with symbols). Due to the mixing with entrained warmer stratospheric air, the enriched vapour layer then remains at this higher isentropic level after the overshoot collapses. The conditions and timescale of the detailed process trapping the enriched water vapour in the TTL was demonstrated in Dauhut et al. (2018). Thanks to a fine temporal resolution of 1 min, they revealed that this process occurs shortly within 20 min."

4. Mixing pathways are not investigated sufficiently in this article to accept Figure 12 as a proven mechanistic diagram. The authors state several times that gravity waves are likely an important, but don't do any investigation into gravity wave overturning. At the resolution of this model, you should be able to observe steep isentropes in the vicinity of the overshoot that indicate gravity wave breaking. And I have detailed other concerns about the amount of mixing from diffusion above. I don't dispute that convection has played an important role in the observed hydration, and the article can still be published as an important case study. But Figure 12 is an overreach based on the analyses done here. I think it should be removed.

Agreed. To better understand about the process along the pathway of hydration patch, we have investigated the evolution of ice particles. In Figure 11e, the ice content (solid lines) and cloud ice (dashed lines) are separately displayed (previously Figure 10). The latter shows that IL includes much reduced amount of ice content than the previous time (green to blue solid lines), but still there is ice content ≥ 1 eq. ppmv and cloud ice ≥ 0.5 eq. ppmv at 12:00 UTC on 7 August (blue dashed line). Meanwhile, the turbulent kinetic energy (TKE) largely increases from 0.1 to 0.3 m^2 s^{-2} in both ML and IL (Fig. 9). Thus we conclude that the turbulent diffusion is the main source for dehydrating ML and IL, but it is not the sole cause. The vapour-scavenging effect plays a role in decreasing the water vapour amount. The manuscript has been improved by including this point. For the sake of clarity, the vertical cross-sections of TKE from 13:00 UTC on 6 August to 06:00 UTC on 8 August have been joined as Figure 9 in the manuscript and further details about TKE and ice microphysics have been included. Considering these, the schematic illustration has been improved.

♣ Page 10, line 268–270

"[...] During 17:00–21:00 UTC (Fig. 9c–e), the large turbulent kinetic energy (TKE) of 0.2–0.9 $m^2\ s^{-2}$ is apparent in a limited area of cloud top (~103°E)."

♣ Page 10, line 276–277

"[...] Within the anvil cloud, still large TKE of 0.2–0.9 $m^2\ s^{-2}$ is seen (Fig. 9f, g)."

♣ Page 10, line 283–285

"[...] The air mass with high tropospheric tracer concentration of 2–40 % consistently exists in ML and IL from 00:00 to 06:00 UTC on 8 August 2017 (Fig. 8k–l), while the TKE of 0.2–0.9 $m^2\ s^{-2}$ exists in wide area between the altitudes of 16 and 18 km (Fig. 9k–l)."

♣ Page 13, lines 352–358

"This can be also seen in the vertical profiles for which the concentration of tropospheric tracer increases at 12:00 UTC on 7 August in both ML and IL (green to blue lines, Fig. 11a) and the water vapour decreases (green to blue lines, Fig. 11d). The two layers become colder by ~3°C (green to blue lines in Fig. 11b), and dehydrated compared to the initial state of 13:00 UTC on 6 August (yellow line in Fig. 11d, e). It includes much reduced amount of ice content (green to blue solid lines in Fig. 11e), but still there exist ice content ≥ 1 eq. ppmv and cloud ice ≥ 0.5 eq. ppmv at 12:00 UTC on 7 August (blue dashed line, Fig. 11e)."

♣ Page 13, lines 364–365

"Also, the vapour-scavenging effect by ice nucleation and growth within IL contributes to reduce the water vapour deriving the dehydration."

♣ Page 13, line 360–362

"[...] Moreover, the turbulent kinetic energy (TKE) increases from 0.1–0.3 $m^2\ s^{-2}$ at 21:00 UTC to 0.2–0.9 $m^2\ s^{-2}$ at 12:00 UTC in ML and IL (~~not shown~~Fig. 9e, i)."

♣ Page 14, line 391–392

"[...] The air mass in ML and IL has large TKE values of 0.5 $m^2\ s^{-2}$ (~~not shown~~Fig. 9l)."

♣ Page 30

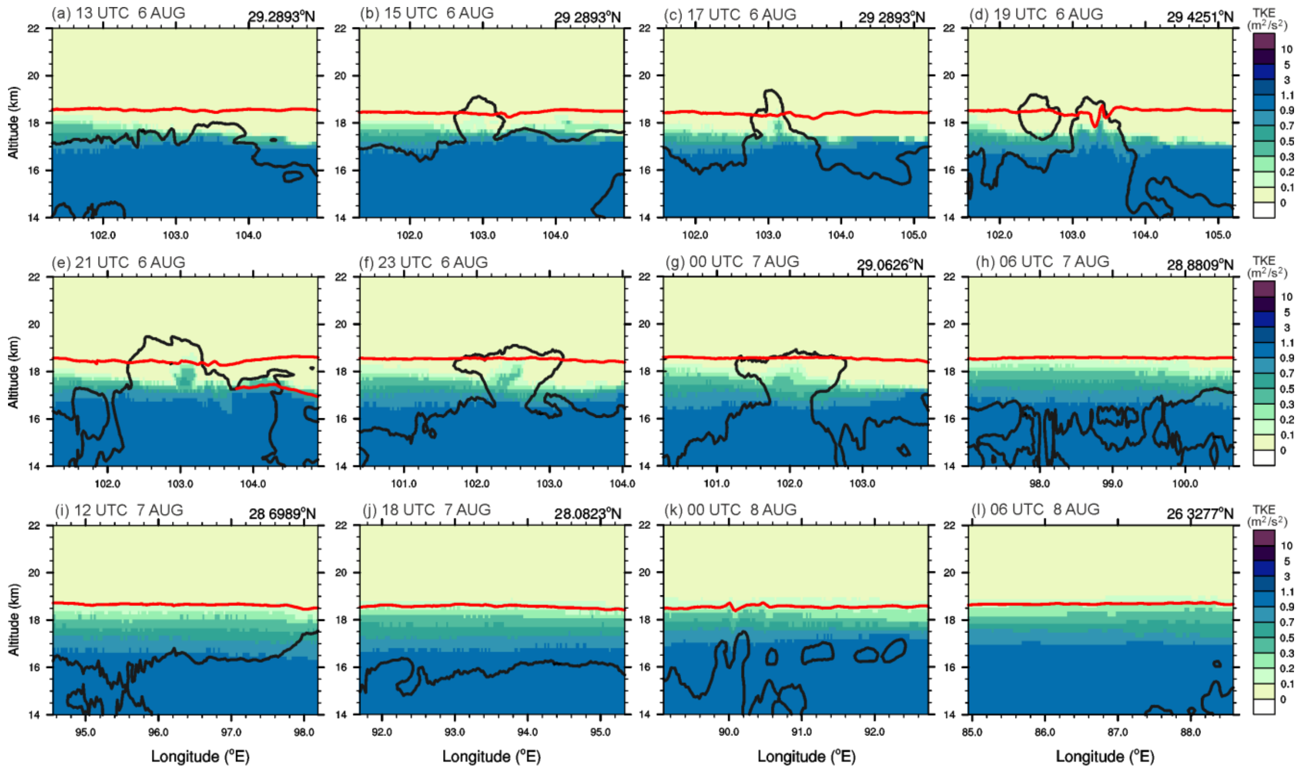


Figure 9. Same as Fig. 6 but for the TKE. The isentropic altitude of 410 K is depicted by the red line.

♣ Page 32

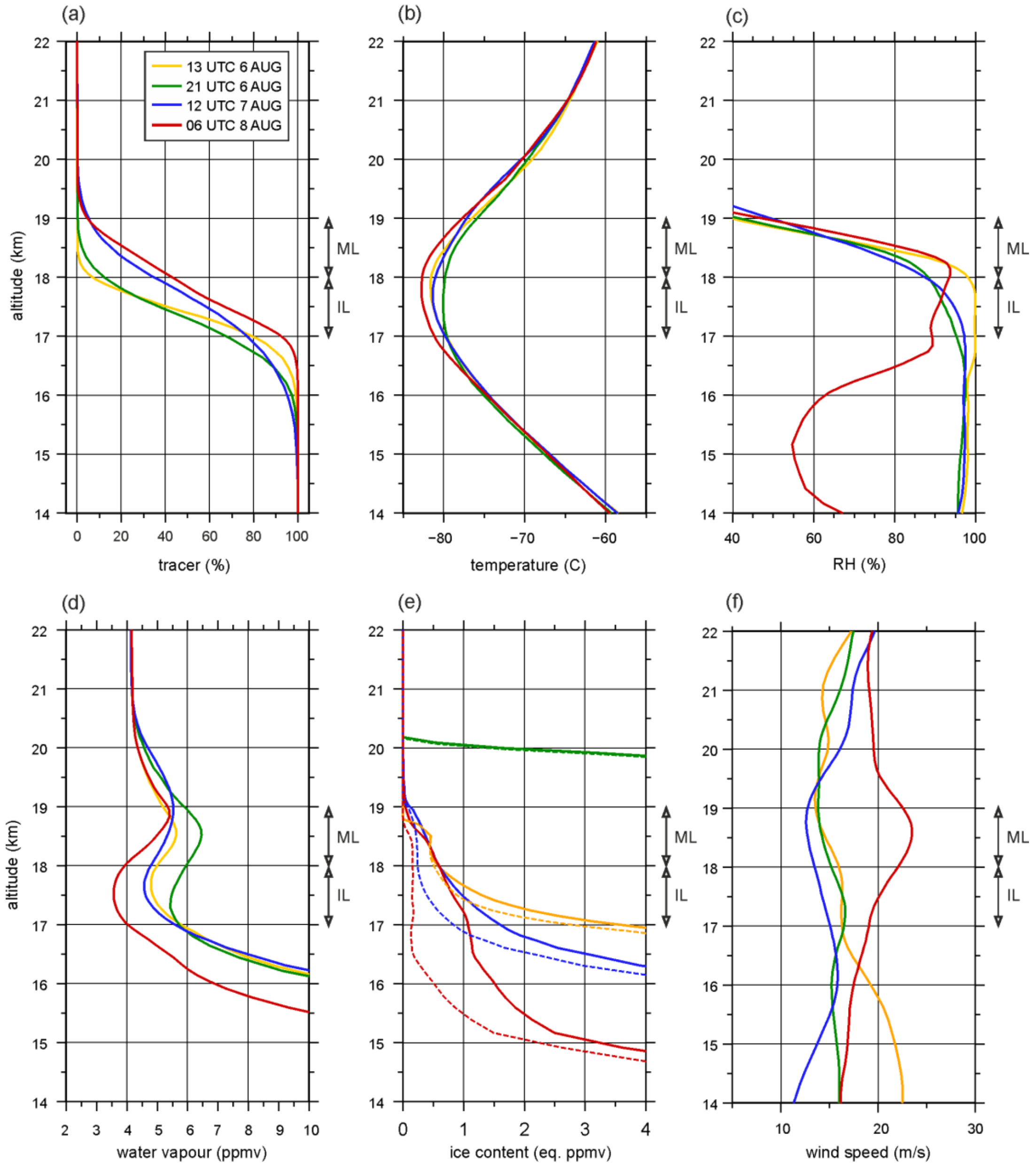


Figure 11. Vertical profiles of (a) tracer (%), (b) temperature (°C), (c) relative humidity (%), mixing ratios of (d) water vapour (ppmv), (e) ice content (eq. ppmv), and (f) wind speed (m s^{-1}) across the hydration patch along the trajectory at 13:00 UTC (yellow line), 21:00 UTC (green line) on 6 August, 12:00 UTC on 7 August (blue line), and 06:00 UTC (red line) on 8 August 2017. The layers of ML and IL are marked by arrows. In (e), the ice content is depicted by solid lines, while the cloud ice are shown by dashed lines.

♣ Page 34

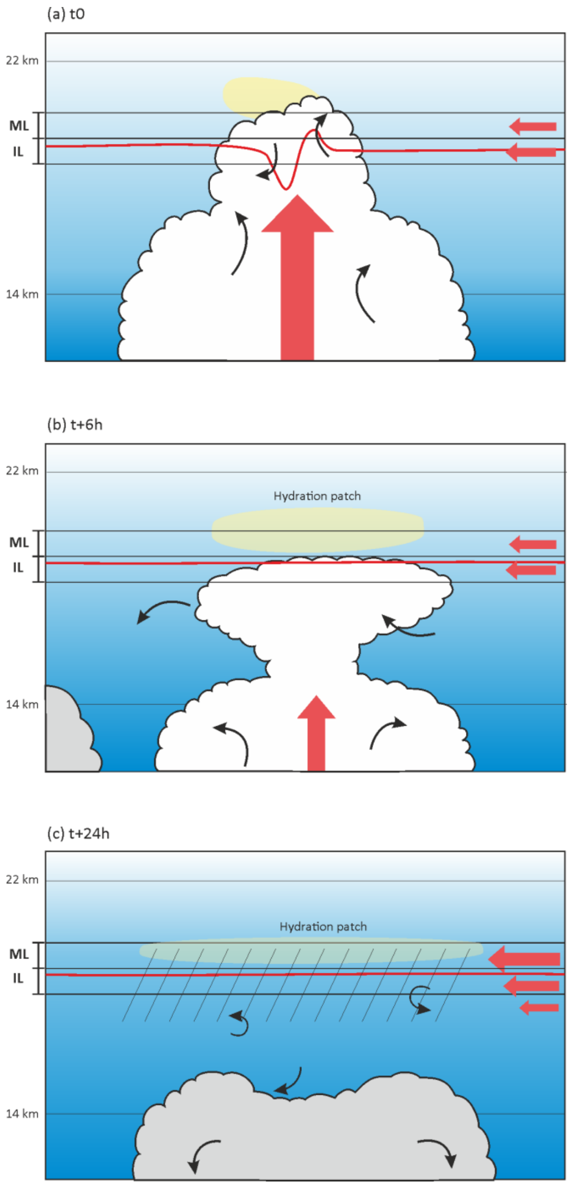


Figure 13. Schematic illustration summarising the hydration process in the TTL during flight #7 of the StratoClim 2017 field campaign. (a) Mixing of the overshoots with the stratospheric air, (b) and (c) turbulent mixing of the hydration patch with the tropospheric air by vertical wind shear. The bottom and top of the TTL, 14 and 22 km, and the moist layer (ML) and ice layer (IL) are represented by the black solid line, and the 410 K isentropic altitude is represented by the red solid line. The main force in the TTL is marked by bold red arrows, while the turbulent eddies in/around the developed and weakened overshoots are described by black arrows. The overreaching water vapour above the cloud top level is indicated by a yellow ellipsoid in (a). The hydration patch is yellow-encapsulated in (a) and (b), and the layer of dehydration by turbulent diffusion and ice microphysics is hatched in (c). The blue shades illustrate the concentration of tropospheric air, showing the increased tropospheric air in the TTL by the turbulent mixing in (b) and (c).

5. besides sensitivity to the turbulent mixing parameterization in this model, and possibly to the numerical diffusion (separate from turbulence parameterizations), other numerical sensitivities may be in play and are not discussed. The most significant of these is the sensitivity to the microphysical parameterization, which could have a significant impact on the hydration processes discussed.
Absolutely. Even our simulation results are reasonable comparing to the observational features, it is true that still some sensitivities of the results to parameterizations, especially the microphysical scheme, should exist. In this study, we used a 1-moment bulk microphysical scheme (Pinty and Jabouille, 1988), which governs the equations of six water categories (water vapour, cloud water, rain water, pristine ice, snow and graupel). For each particle type, the sizes follow a generalized Gamma distribution while power-law relationships allows the mass and fall speed to be linked to the diameters. In a future study, conducting a simulation with a 2-moment microphysical scheme that considers the mass and number concentration of hydrometeors, as well concentration of aerosols, would be worthwhile. This point has been included in the manuscript.

♣ Page 17, lines 464–467
"[…] Also, additional numerical simulations with a 2-moment microphysical scheme that considers mass and number concentration of hydrometeors and aerosol together with options in the turbulent scheme (e.g., 1D against 3D formulations, Machado and Chaboureau, 2015) will be worthwhile to study the impact on the results."

Machado, L. A. and Chaboureau, J. P.: Effect of Turbulence Parameterization on Assessment of Cloud Organization. Mon. Wea. Rev., 143, 3246–3262, https://doi.org/10.1175/MWR-D-14-00393.1, 2015.

Additional comments

Line 35: "…Middle East and is located on the edge…"
Corrected.

Line 43: "…relatively high at about 4.2 ppmv…"
Corrected.

Line 56: "The most energetic one forms…" Energetic what? I assume you mean convective core, but this phrasing is clunky.
It has been rephrased to "They eventually form…".

Line 59: I realize your list of prior studies analyzing water vapor injection by convective overshoots is not meant to a complete list, but some recent articles are missing from your list and I want to make sure you have incorporated their findings into your assessment:
1. Homeyer, C.R., et al. (2014), Convective transport of water vapor into the lower stratosphere observed during double- tropopause events, J. Geophys. Res. Atmos., 119, 10, 941–10,958, doi:10.1002/2014JD201485.
2. Homeyer, C.R., J.D. McAuliffe, and K.M. Bedka, 2017: On the development of above-anvil cirrus plumes in Extratropical convection. J. Atmos. Sci., 74, 1617–1633, https://doi.org/10.1175/JAS-D-16-0269.1
Thank you for listing the recent articles. These have been cited in the manuscript as well as two other mid-latitude studies, but over Europe.

Funatsu, B. M., Rysman, J. F., Claud, C., and Chaboureau, J. P.: Deep convective clouds distribution over the Mediterranean region from AMSU-B/MHS observations, Atmos. Res., 207, 122−135, https://doi.org/10.1016/j.atmosres.2018.03.003, 2018.
Rysman, J.-F., Claud, C., Chaboureau, J. P., Delanoë, J. and Funatsu, B. M.: Severe convection in the Mediterranean from microwave observations and a convection-permitting model, Quart. J. Roy. Meteor. Soc., 142, 43−55, https://doi.org/10.1002/qj.2611, 2016.

Line 79: "…that was measured by aircraft in connection to a convective overshoot."
Corrected.

Line 80: "…and spaceborne observations as well as…"
Corrected.

Line 160: The hydration patch is "chased" back in time: You need to include a more quantitative explanation of exactly how the location of the hydration patch was identified going back in time.
For the sake of the clarity, the description about the hydration patch has been further improved in the manuscript.

♣ Page 6, lines 160–164
"[…] The hydration patch is chased visually back in time every hour from 06:00 UTC on 8 August to 13:00 UTC on 6 August 2017, considering the prevailing wind direction and speed at 410 K isentropic altitude. At 14:00 UTC, a large amount of water vapour (≥ 6.6 ppmv), that is injected by the convective overshoot in the Sichuan basin, starts to appear at this altitude, generating a hydration patch. With the dominant east-northeasterlies (15–20 m s^{-1}), it travels to the south of Kathmandu."

Also, Figure 4 has been improved joining the horizontal wind at the altitude of 19 km (nearly equivalent to 410 K isentrope) at 06:00 UTC on 8 August. The dominant wind is east-northeasterlies at the speed of 15–20 m s^{-1}. The wind direction corresponds to the pathway of the hydration patch from the Sichuan basin at 14:00 UTC on 6 August (Fig. 4e) to the south of Kathmandu at 06:00 UTC on 8 August (Fig. 4a). During 14:00–21:00 UTC on 6 August, the hydration patch moved westward with weak easterly wind (about 10 m s^{-1}). Then during 00:00–06:00 UTC on 8 August, the hydration patch moved farther southwest, to the south of Kathmandu with the strong east-northeasterlies (about 25 m s^{-1}).

♣ Page 26

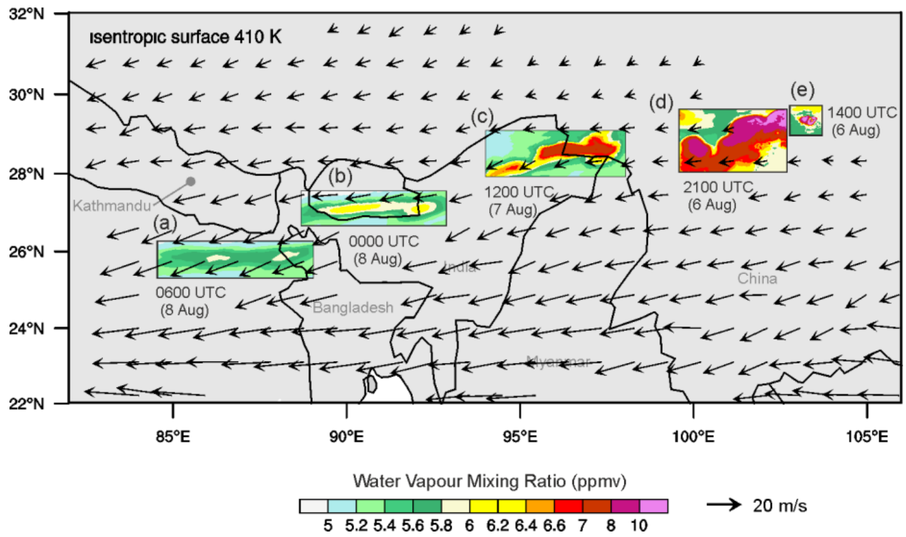


Figure 4. Target moist patch. Horizontal distribution of water vapour mixing ratio at 410 K isentropic altitude at (a) 06:00 UTC, and (b) 00:00 UTC on 8 August, (c) 12:00 UTC on 7 August, (d) 21:00 UTC and (e) 14:00 UTC on 6 August 2017. The horizontal wind at the altitude of 19 km (about 410 K isentrope) at 06:00 UTC on 8 August is displayed by vectors.

Line 223-225: Looking at Figure 5, there do seem to be some isolate overshoots at 13 UTC, as there are some areas of very cold brightness temperatures.

Corrected.

Figures 6, 7, and 8: The small black lines are not labelled, but they look like wind vectors. These should be removed because they are not discussed, and they make these plots hard to read.

For the sake of readability, the wind vectors in Figures 7 and 8 are removed while remaining in Figure 6 to show the updraughts in the overshooting convection. Figure 6 has been revised by changing the colour of cloud boundary to white and the wind has been stated in the manuscript.

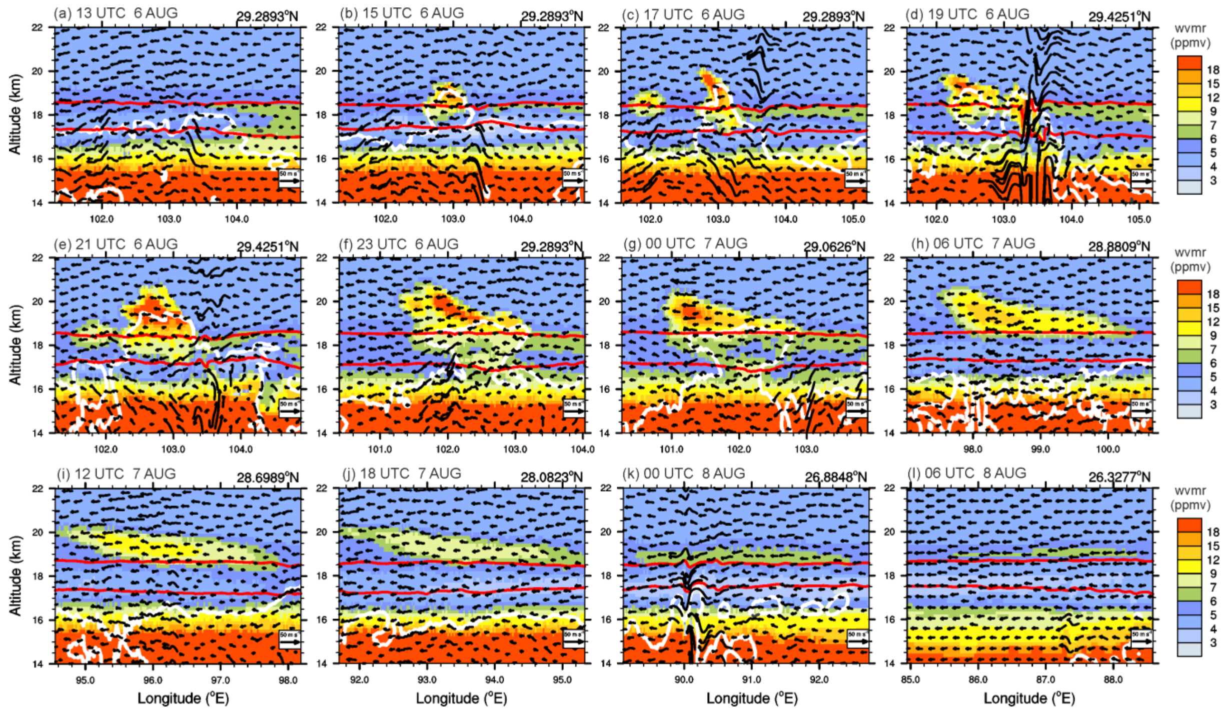


Figure 6. Vertical cross-sections of water vapour mixing ratio (shading) and wind (vectors) (a) 13:00 UTC, (b) 15:00 UTC, (c) 17:00 UTC, (d) 19:00 UTC, (e) 21:00 UTC, (f) 23:00 UTC on 6 August 2017, (g) 00:00 UTC, (h) 06:00 UTC, (i) 12:00 UTC, (j) 18:00 UTC on 7 August 2017, and (k) 00:00 UTC and (l) 06:00 UTC on 8 August 2017. The isentropic altitudes of 380 and 410 K are depicted by the red lines. The latitude (°N) of west-east oriented cross-section line is indicated at the upper right of each panel. The cloud boundary (mixing ratio of ice content of 10 mg kg^{-1}) is contoured by the white solid line.

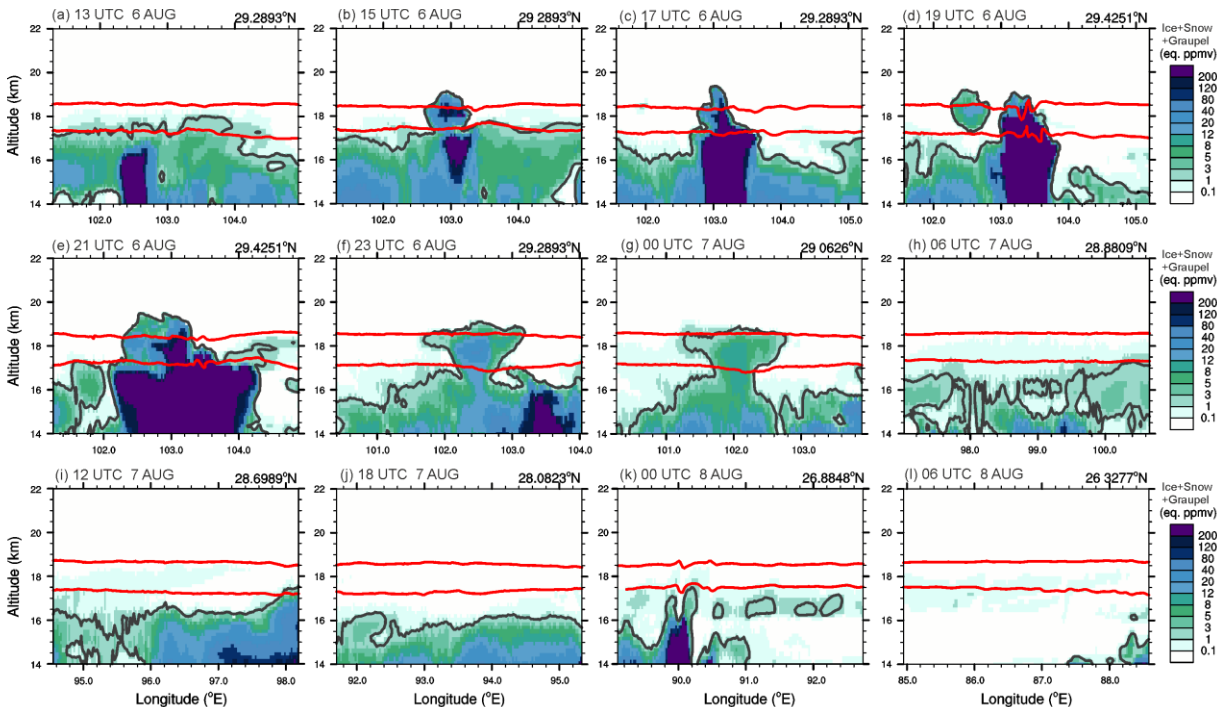


Figure 7. Same as Fig. 6 but for the ice content. The isentropic altitudes of 380 and 410 K are depicted by the red lines.

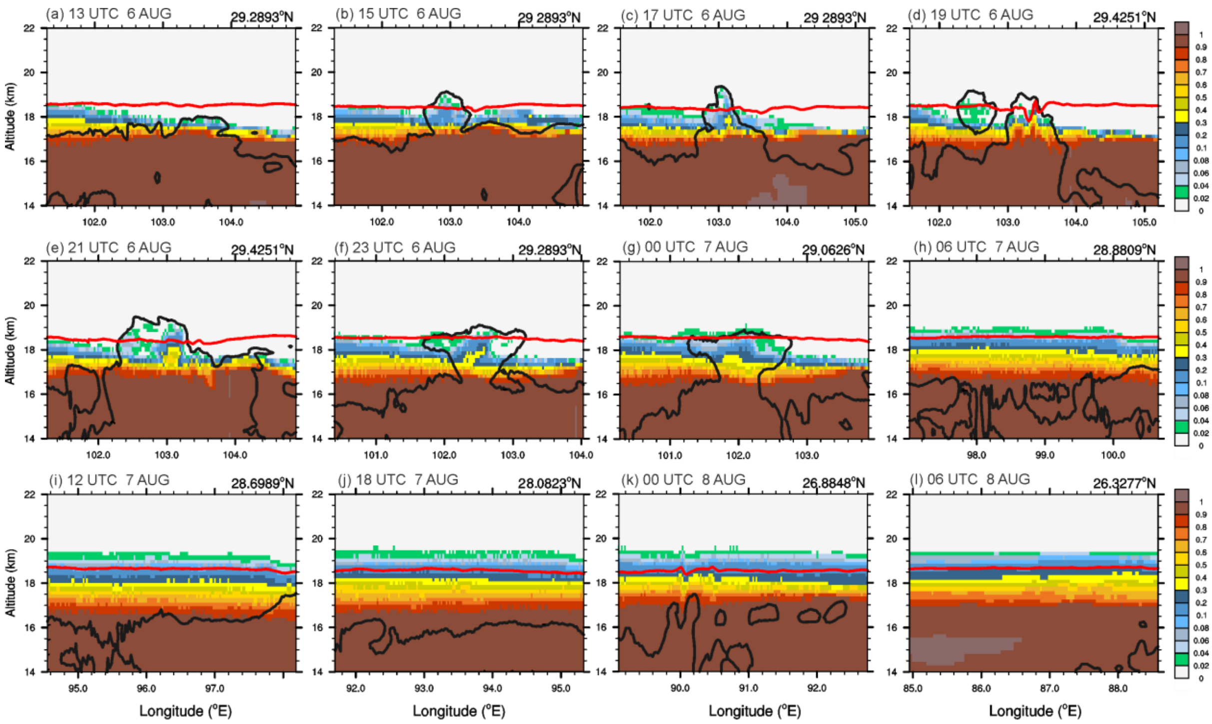


Figure 8. Same as Fig. 6 but for the tracer (%). The isentropic altitude of 410 K is depicted by the red line. The main changes of the tropospheric tracer by convective overshoots is marked by downward arrows.