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Atmospheric Chemistry and Physics Discussions

# *Interactive comment on* "Impact of tropical land convection on the water vapour budget in the Tropical Tropopause Layer" *by* F. Carminati et al.

**F. Carminati et al.**

fabien.carminati.01@gmail.com

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We would like to thank the third referee for addressing us his/her recommendations on the topics that needed improvement in this study. His/her questions regarding the uncertainties inspired us the analysis of the most and least convective cases that we believe substantially improve the discussion.

MAJOR COMMENTS:

(1) Relating the 56 hPa (and even 100hPa) water vapor pattern (Fig. 2 and Fig 6) to deep convection is likely incorrect. The uncertainty in the water vapor retrieval at 100hPa and 56 hPa is 10% or larger. Any changes (e.g. Day-Night difference) less than 10% are insignificant. Note the 10% MLS retrieval uncertainty including biases,

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which cannot be reduced by averaging.

RESPONSE:

It is right that, unlike the accuracy, MLS precision is about 10% in the TTL and LS cannot be reduced by averaging a large number of data. Nevertheless, most of the results presented in our study rely on the Day-Night difference, meaning that all systematic errors, including biases, are greatly reduced, assuming that daytime and night-time have similar systematic errors.

Because the quality of our analysis is our first preoccupation, and to answer all three referees having expressed concerns regarding the significance of the data, we dedicated a whole new section in the discussion regarding the uncertainties. In summary, we emphasized three main points: 1) the averaging kernels peaking at 177, 100, and 56 hPa are mostly independent and cover at their full width at half maximum the layer of interest, namely, UT, TTL and LS, respectively, 2) positive D-N above continent is not an artifact of the a priori, which a contrario may cause underestimations, and 3) |D-N|s greater than 10% represent about 80% of all available D-Ns at 177 hPa, 50% at 100 hPa and 10% at 56 hPa in summer. In light of the third point, we conclude that the small D-N amplitude in the TTL and LS results from the average of a large number of insignificant days (D-N close to 0), but does not change our conclusions based on the variation in sign and intensity between different regions and not on absolute quantities. In addition, we implemented a comparative analysis between the most convective scenario (|D-N| at 177 hPa greater than 20%) and the least convective scenario (|D-N| at 177 hPa smaller than 5%). For further details, please refer to the responses to referee #1, major comment as well as minor comment number 9.

MAJOR COMMENTS:

(2) Using 6 small box regions (Fig 2 upper-right panel) near the tropics to come up with a conclusion (e.g. line 20 on page 33056) about stronger convection and more efficient moistening in the Southern Hemisphere is misleading. In the Northern Hemisphere

(NH) deep convections are mostly over South Asia and Central America monsoon regions during JJA, while in the Southern Hemisphere (SH) deep convections are over South America, Central Africa and Western Pacific/maritime continent during DJF. The small boxes are all near the SH convection regions and thus are stronger during DJF. Away from the tropics, you will find the deep convection and water vapor moistening are the strongest in the NH, not SH (e.g. Sample-Figure 1).

RESPONSE:

The wording is effectively misleading. This study focuses on tropical land convection and the conclusions cannot be extrapolated to extra tropical latitudes. As mention by the referee, the regions of deeper convection are away from the tropics in the NH. It is right that Central America and South East Asia are also places of strong convection, but at the edge of the tropic and under the strong influence of their adjacent seas (please see response to referee #2, minor comment number 22). Monsoon convection has different origins, characteristics and extends on larger scales than the tropical land convection subject of our study. These regions require an analysis on its own, and should be treated in a different paper. This is out of the scope of this paper.

Our boxes are located where the summertime D-N presents the strongest negative signal, synonym of continental convection, (e.g. south and north tropical America and, south and north tropical Africa), the maritime continent and western pacific playing the role of control relative to oceanic regions. Our conclusions are thus relative to north versus south tropical land, principally represented by the South American and African continents. For this reasons, we replaced Southern and Northern Hemispheres by Southern and Northern tropics, but remain faithful to the conclusions of this study.

MAJOR COMMENTS:

(3) This study focused on the regional features but overlooked the influence of large-scale dynamics. Even though some of the regional patterns seen at 100hPa and 56 hPa may be real, they are not necessary related to the convection below. Unlike the

ice water content (IWC), water vapor mixing ration (H2O) near the tropopause and lower stratosphere are strongly influenced by the large-scale dynamics/transport due to its long lifetime. Regional scale convections, such as those over the South America and Africa, do have an influence on H2O up to about 150 hPa altitude. At pressure $\leq$ 100hPa and in the lower stratosphere (e.g. at 56 hPa), the spatial distributions and time evolution of H2O, even at regional scale, are strongly influenced by the H2O transport (horizontal and vertical). For example, The following Sample-Figure 1 shows the time evolution of zonal mean H2O at 100 hPa and 215 hPa pressure levels. The patterns of 215 H2O follows the seasonal cycle of deep convection, while the seasonal cycle in 100 hPa H2O is dramatically different, due to horizontal transport of H2O into higher latitudes.

RESPONSE:

The manuscript indeed lacked a discussion on the impact of horizontal transport. As mentioned in the response to the comment number 1, we discriminated the significantly convective days, associated to a |D-N| at 177 hPa greater than 20%, to the insignificantly convective days, that we relate to a |D-N| at 177 hPa smaller than 5%, in order to understand what part of the H2O variability cannot be attributed to the convection. From this analysis, we were able to highlight a layer of large variation in the bottom of the TTL (121-100 hPa) present in the least convective scenario and then not attributable to convective vertical transport. Characterized by a strong night-time moistening, this variability can only result from advection from outside the considered box. However, the transport must occur on short timescale from the source to the box, suggesting an origin from neighboring convective areas, otherwise mixing would progressively erase the Day-Night difference. Around 82 hPa, a band of positive D-N is measured in absence of convection indicating that, like in oceanic areas, the heating cycle of cirrus cloud can lead to a daytime moistening. In the LS, the negative D-N between 46 and 56 hPa also suggests possible advection from neighbouring regions.

The main conclusion of this study is that deep convection is a major driver of the diurnal

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variability of H2O in the TTL and LS, but also that convection does not significantly affect the seasonal variability, which is under the influence of the seasonal variation of temperature at the tropopause. Large-scale transport does not have a significant role at timescale of the order of the hour and thus, cannot be held responsible for diurnal variability. For this reason it is not further investigated. The following paragraph has been added to the discussion:

"For insignificantly convective cases, we assume that the convection is not responsible for the variability above 177 hPa. We observe a D-N distribution in the TTL similar to that of oceanic areas in Fig. 6b. A negative layer, at approximately 121 – 100 hPa, is surmounted by a positive D-N extending from 100 to 68 hPa, with maxima at 82 hPa coincident in time and pressure with the temperature minimum. Characterized by a strong negative D-N, the variability at the bottom of the TTL can only result from advection from outside the box. However, the transport must occur on short timescale (a few hours) from the source to the box, suggesting an origin from neighbouring convective areas; otherwise, mixing would progressively eliminate the difference between the day and night. In the LS, the negative D-N between 46 and 56 hPa also suggests possible advection from neighbouring regions."

MAJOR COMMENTS:

(4) The discussion of “tape-recorder” features (e.g. the phase-lag) in Fig 4 and Fig 5 are confusing, or at least not clear. The traditional “tape-recorder” refers to the vertical H2O transport into the stratosphere in the tropics [Sample-Figure 2].

RESPONSE:

We rephrased it to clarify this point:

"In the LS, H2O is vertically transported in a slow ascent by the Brewer-Dobson circulation (Mote et al., 1996). This mechanism, referred as ‘tape recorder’, causes the wet and dry air parcels to be progressively time-lagged as they gain altitude."

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MAJOR COMMENTS:

In the tropics, the seasonal cycle is relatively weak at below 147hPa. The tropopause and stratospheric H2O are modulated both by temperature and large-scale transport. The seasonal variations of sub-tropical H2O are influenced by the summertime deep convections. In the northern sub-tropics [Sample-Figure 3], the JJA deep convections from South Asia and Central America monsoon can directly deposit (overshoot) H2O into the tropopause above 147 hPa altitude, followed by slow ascend into the lower stratosphere. At 56hPa level, the peak H2O has been transported away from the convection centers.

RESPONSE:

We agree with the referee that the seasonal H2O variation at the tropopause level and above is modulated by the temperature and large-scale transport. However, the diurnal cycle of H2O consistent with the positive D-N measured by MLS above continents results from the diurnal cycle of temperature (±0.6 K of maximum magnitude between 80 and 40 hPa, Khaykin et al., 2013) itself caused by the deep convection. This effect is thus independent of the origin of H2O (whether the H2O background at 56 hPa origins from the underneath layers or has been transported from the other hemisphere) but modulates the in situ H2O background. Arguments relative to these points have been added in the discussion as follows:

"At 56 hPa, the daytime continental hydration cannot be attributed to the direct injection of ice crystals, which caps, on average, at 82 hPa. The positive D-N, however, is consistent with the temperature diurnal cycle as presented by Khaykin et al. (2013), and attributed to non-migrating tides and convective updraft of adiabatically cooled air, of maximum amplitude in the LS. H2O potentially turns into ice with the afternoon temperature drop, and then sublimates the next morning when the temperature rises. Note that it is possible that the information captured by the AK peaking at 56 hPa comes from the 70-60 hPa region, where colder temperature than that found at 56 hPa would favour this process. Remarkably, the geographical extension of the brightness temperature diurnal cycle over the ocean westward of South America and Africa revealed by Yang and Slingo (2001) and attributed to the propagation of gravity waves, can explain the positive D-N observed in Fig. 2 over the same places. "

MAJOR COMMENTS:

In the southern sub-tropics [Sample-Figure 4], the DJF deep convections from Western Pacific, South America and Africa do not penetrate the tropopause. The cold temperatures at top of the convection, especially in the Western Pacific, are the cause of low water vapor near tropopause. The maxima H2O above 100hPa altitude [Sample-Figure 4] are phase-shifted to JJA, which indicate the H2O there are transported from the north. How these large-scale features impact the regional scale (e.g. the 6 small boxes in Fig 2) H2O at 100hPa and 56 hPa are not investigated and discussed in this study.

RESPONSE:

It is true that on a zonal average, H2O anomaly in the SH as shown in Sample-Figure 4 is weaker than the NH anomaly in Sample-Figure 3, but it can be explained by two reasons. First, the overshooting convection is more frequent over land than over ocean (Liu and Zipser, 2005). Consequently, the 15°S-30°S latitudinal band used by the referee is naturally biased because it covers less continental area than the 15°N-30°N used for Sample-Figure 3. Secondly, we showed, in agreement with Liu and Zipser (2005, 2009) that the strongest convection in the SH is localized between 0°S-20°S, an area mostly missed by the referee analysis.

More specifically, we showed that convective areas by their nature (land, ocean, subtropical, extra-tropical, monsoon, north, south) cannot be compared at large scale but requires a regional approach. Using our boxes to differentiate the different tropical regions demonstrate that indeed convection in western Pacific does not reach the tropopause level but South American and African deep convection have the potential to impact the TTL up to about 82 hPa in average (e.g. Fig. 8 in the final manuscript). Furthermore, the UT anomaly at regional scale is significantly stronger above south tropical land than above north tropical land.

MAJOR COMMENTS:

(5) In many places in the paper, the authors discuss “diurnal cycle”. Since MLS only make measurements twice a day at 1:30am and 1:30pm, we can only show “Day-Night” difference, but cannot actually resolve the diurnal cycle. The H2Oc curve in Fig 1 is for UT (upper troposphere) only, which is not necessary true in the tropopause and lower stratosphere.

RESPONSE:

This is true, we replaced ‘diurnal cycle’ by ‘Day-Night difference’ or simply ‘D-N’ when referred to MLS.

MINOR COMMENTS:

(1) Page 33056 line 20: You should at least change “Southern Hemisphere” to “southern tropics”, because the results from small boxes shown Fig 2 upper-right panel can not represent the entire SH.

RESPONSE:

‘Southern Hemisphere’ has been replaced by ‘southern tropics’.

MINOR COMMENTS:

(2) Page 33061 line 14: Should be 215 hPa, not 220 hPa.

RESPONSE:

True, it has been modified.

MINOR COMMENTS:

(3) Page 33061 line 25: Please specify which screening are used for this study, 2$\sigma$ or 3$\sigma$? I recommend the 3$\sigma$ screening should be used.

RESPONSE:

The screening method is called "2$\sigma$-3$\sigma$ method" and consists in an iterative computation of the mean IWC for 10° latitude band rejecting value greater than 2$\sigma$ followed by the selection of all IWC measurements greater than this mean + 3$\sigma$. This method is suggested in the MLS Version 3.3 Level 2 data quality and description document https://mls.jpl.nasa.gov/data/v3_data_quality_document.pdf and detailed by Wu et al. (2008).

MINOR COMMENTS:

(4) Page 33062 line 1: Should be 215 hPa, not 220 hPa.

RESPONSE:

True, it has been modified.

MINOR COMMENTS:

(5) Page 33062 Section 2.2: As discussed above, MLS observations cannot resolve diurnal cycle, most discussions of the diurnal cycle differences here Page should be changed to day-night differences.

RESPONSE:

We replaced 'diurnal cycle' by 'Day-Night difference'.

MINOR COMMENTS:

(6) Page 333063 line 3: Note 5-10% is not a significant during to MLS uncertainty of 10%.

RESPONSE:

Please refer to major comment 1.

MINOR COMMENTS:

7) Page 33063 line 19: Again, at least change “Southern Hemisphere” to “southern tropics” and change “Northern Hemisphere” to “northern tropics”

RESPONSE:

Hemisphere has been changed into tropics.

MINOR COMMENTS:

(8) Page 33063 line 27-28: Change “amplitude of the IWC diurnal cycle. . .” to “the day- night difference. . .”, since MLS can not resolve the diurnal cycle. (The amplitude of the diurnal cycle could be larger than the day-night difference observed by MLS).

RESPONSE:

We replaced ‘diurnal cycle’ by ‘Day-Night difference’.

MINOR COMMENTS:

(9) Page 33065 line 6: Change “. . .over land areas” to “. . .over tropical land areas”.

RESPONSE:

We modified the wording as suggested.

MINOR COMMENTS:

(10) Page 33066 line 5: Change “Water vapour in the Southern Hemisphere” to “Water vapour in the southern tropics”.

RESPONSE:

We modified the wording as suggested.

MINOR COMMENTS:

(11) Page 33069 line 2: Change “diurnal variation” to “day-night difference”.

RESPONSE:

We modified the wording as suggested.

MINOR COMMENTS:

(12) Page 33070 line 1-4: This sentence is not clear.

RESPONSE:

The whole paragraph has been modified, please refer the response to referee #2, comment number 19.

REFERENCES:

Liu, C., and E. J. Zipser (2005), Global distribution of convection penetrating the tropical tropopause, J. Geophys. Res., 110, D23104, doi:10.1029/2005JD006063.

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