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Date: Monday March 31st, 2014

To: Dr. Peter Haynes,
ACP Editor,
phh@damtp.cam.ac.uk

Re: Manuscript number acp-2013-902

Dear Editor,

The co-authors and I are very grateful for the interest that you pay to this study entitled "Impact of Tropical Land Convection on the Water Vapour Budget in the Tropical Tropopause Layer", as well as the time that you dedicate to the editing process. We also appreciated the comments and suggestions made by the referees that helped us to substantially improve the quality of our study. We addressed each of their interrogations a point-by-point response as presented below. A List of the relevant changes in the manuscript finalizes this document.

Sincerely,

Fabien Carminati

Response to Referee #1

We would like to thank the first referee for his/her rightful comments that helped us to substantially improve the quality of our study. Also, we really appreciated that the referee returned its review ahead of time.

General comments:

This paper follow the line of study by Liu and Zipser 2009 and focusing on the day vs. night differences in the MLS water vapor retrievals in the northern and southern hemisphere. The results are interesting, especially on the stronger day vs. night difference in the southern TTL over land, as well as the level of the impact of convection indicated by the day vs. night water vapor differences. These results are firm evidences of the impact of deep convection to the TTL over land. Manuscript is well written. Therefore, I recommend accepting the paper for publish after a few minor points being addressed.

Recommendation: accept with minor revision

MAJOR COMMENTS:

One main question I have is the uncertainty of the retrievals at 100 hPa and above. Day vs. night water vapor differences from mean values in Figure 6 are very small at levels above 100 hPa, I am wondering how robust is these results.

The accuracy of the results presented in our study is naturally of high priority, and all three referees pointed out the very small variability showed in the TTL and the LS. Hence we conducted extra efforts to better determine the significance of the day versus night variations.

We first considered the MLS averaging kernels (AKs) in the pressure domain of interest. AKs at the equator and at 70°N of each MLS products are provided on the NASA Jet Propulsion Laboratory webpage (https://mls.jpl.nasa.gov/data/ak/). Figure A shows the MLS H_2O AKs at equator between 250 and 30 hPa. Dashed black lines represent the 177, 100 and 56 hPa levels. For each level, we colored the corresponding AK that peaks exactly at the pressure of interest. The 177 hPa AK mostly covers the UT with a full-width at half-maximum (FWHM) from 230 to 125 hPa. The 100 hPa AK covers the TTL region from 125 to 80 hPa. Finally, the FWHM of the 56 hPa AK extends from 70 to 45 hPa in the LS. Thus, each of the three highlighted AKs peaks and covers the layer of interest (UT, TTL and LS) with minor overlapping at half maximum. Thereby, we can assume that the three layers are independent in the Optimal Estimation theory since the three AKs cover the region 230-45 hPa with no overlapping at the half-maximum level.

The MLS a priori has also been analysed. MLS a priori is a combination of climatology and operational meteorological data (Livesey and Snyder, 2004) so that for every retrieved H_2O profile corresponds an a priori profile. One year of H_2O a priori, from January to December 2012, was treated with the same methodology as H_2O. Figure B shows the per cent relative difference between daytime and night-time MLS H_2O a priori at 177, 100 and 56 hPa in DJF and JJA in the tropics. Globally, the a priori D-N is well below 1% at all levels. Nonetheless, the distribution is not uniform. Localized areas can also reach a D-N close to -2%, as in Southern Brazil at 100 hPa. Tropical lands (e.g. South America and Africa) have a negative or nearly null a priori D-N at all levels. This implies that the positive H_2O D-N measured in the TTL and LS is not an artifact generated by the a priori and its amplitude is certainly underestimated. Conversely, in the UT, the negative H_2O D-N above continents in DJF and JJA is probably slightly overestimated by at most 2%.

Thus, we showed that H_2O measurements at 177, 100 and 56 hPa were independent with respect to each other, and that the a priori does not generate artificial positive values in the D-N above continents. Nonetheless, uncertainties in MLS H_2O accuracy and precision (7% and 10%, respectively at 83 hPa) remain to be understood. In the case of our study, it is important to understand the meaning of these uncertainties and consider them separately. On the one hand, the accuracy that can be viewed as a random error is considerably reduced in our study, because, between 2005 and 2012, we average a large number of data (~14,000 profiles in each 10°x10° grid bin for the whole period). On the other hand, the precision, reflecting the systematic error (including biases), is not reducible by averaging the data. However, when the difference between two datasets with the same systematic error is calculated, this systematic error is theoretically removed. Assuming that the daytime and the night-time MLS precisions are similar, we can expect that the systematic error is minimized in the D-N analyses. It is also important to acknowledge that values of a large number of H_2O D-N are close to zero. They represent the insignificant cases and produces an underestimation of the D-N amplitude. The arising question is then: what is the proportion of significant-insignificant cases in the averaged D-N?

To answer this question, we evaluated the number of days when both an H_2O average daytime and night-time profile were available (consisting typically of ~6 profiles each) in the African and South American regions, and estimated the percentage for which the D-N was significant. We consider to be significant all |D-N| is greater than 10%. Figure C shows the percentage of days when the D-N is significant at 177, 100 and 56 hPa in South tropical America. In total, there are 1637 out of 2921 days (2005-2012 period) when both daytime and night-time are available. Among these, about 80% present a significant D-N at 177 hPa, about 50% at 100 hPa and about 10% at 56 hPa, during the convective season (DJF). The statistics are similar in south tropical Africa and their counterpart in the NH (not shown). The small amplitude of D-N in the TTL and the LS is thus the result of the average of a large number of D-N that are close to zero, but the non-negligible amount of significant cases allows us to safely rely on the sign of the D-N.

This study aims to be a qualitative analysis of the H_2O variability, because, even if MLS was able to measure the finest variation, it does not sample at the maximum of convection, but rather an initial state (at 13:30 LT at the beginning of the convection cycle) and a final state (at 01:30 LT toward the end of the cycle). Therefore, we can only conjecture what happen in-between.

MINOR COMMENTS:

1. P33056, L10, This is a quite long sentence. Might be helpful to break into a few shorter sentences. Why TTL is defined as 121-68 hPa? Does full oceanic areas share the same diurnal cycle as maritime continents?

It is right that the TTL has not been defined yet. Also, land and ocean have a different cycle. As suggested we broke and reformulated the sentences as follows:

In the tropical upper troposphere (177 hPa), continents, including the maritime continent, present the night-time (01:30 Local Time) peak in the water vapour mixing ratio characteristic of the H_2O diurnal cycle above tropical land. The western Pacific region, governed by the tropical oceanic diurnal cycle, has a daytime maximum (13:30 Local Time). In the TTL (100 hPa) and tropical lower stratosphere (56 hPa), South America and Africa differs from maritime continent and western Pacific displaying a daytime maximum of H_2O.

2. P33056, L15, the amplitude of water vapor diurnal cycle larger does not directly indicate a stronger convection. Water vapor variations due to the convective detrainment may also depend on the surrounding ambient water vapor concentration (how dry it is). What if the southern LS is dryer?

A climatology of the relative humidity background shows that there are few or no differences at least in the UT between our 8 boxes. (For further details please refer to the response to referee #2 minor comment number 19.)

In addition, the amplitude of the difference between the daytime and the night-time H_2O concentration is compared in relative terms (day versus night, with respect to the daytime) so that even if one hemisphere was drier than the other, the relative amplitude remains an adequate tool to compare Northern and Southern hemisphere. Note that, a greater amplitude in the Southern hemisphere than in the Northern in the temperature diurnal cycle induced by convection was reported by Khaykin et al. (2013), as mentioned in section 2.4. Nonetheless, it is right that the largest differences between Northern and Southern tropics are observed in the UT and, to a lesser extent in the TTL, so we modified the sentence as follows:

In addition, the relative amplitude between day and night is found to be systematically higher by 5–10% in the south tropical UT and 1-3% in the TTL than in the northern tropics during their respective summer, indicative of a more vigorous convective intensity in the southern tropics.

3. P33059, L20, please mention that the boxes used in this study are shown in Figure 2.

The Fig. 2 [in the final manuscript] is updated and the text modified as follows:

We also focused on restricted areas of the north tropical and the south tropical South America, Africa, maritime continent (where the convection was shown to be most intense by Liu and Zipser, 2005) and Western Pacific (see Fig. 2).

4. P33061, L1-3, Would the definition of the TTL change your conclusions? Note that 121-68 hPa basically include the upper troposphere and lower stratosphere. With low vertical resolution, this is > 6 km depth.

An exact definition of the TTL is not clearly established, mostly because the TTL does not present the same characteristics (depth, processes involved or entry level) depending if studied in maritime area or in continental area. Some defines it as the upper tropospheric layer under influence of the LS plus the lower stratospheric layer under influence of the UT. It is thus not surprising that what we defined as TTL (121-68 hPa) include what could be seen as the upper part of the UT and the lower part of the LS. In this study we chose the layers for which the D-N demonstrates a change in variability and then in the processes involved. As seen in Figs. 6 and 7 [in the final manuscript] the D-N behavior is different to those in the UT and in the LS between 121 and 68 hPa. Finally, we showed that the AKs peaking at 177, 100 and 56 hPa are not overlapping at their half-maximum. The three layers are thus independent.

5. P33062, 14, both MAM and SON are active seasons for deep overshooting convection in tropics (Liu and Zipser 2005).

It is right that Liu and Zipser (2005) showed a semi-annual cycle in the convective season. In our study however, we point out the importance to differentiate the most convective periods in the NH and the SH. The strong negative D-N in the UT (Fig. 2 in the final manuscript), the IWC occurrences (Fig. 5 in the final manuscript) and the H_2O concentration (top panel Figs. 6 and 7 in the final manuscript), show areas of intense convection well established in the South between 0 and 20°S (North, between 0 and 20°N) in DJF (JJA). MAM and SON are transition periods during which the convective systems move South to North and conversely, so that the maximum of convection is found at the equator. Extended seasons (DJFM and JJAS) have been studied (not shown) but no significant differences with DJF and JJA were found.

6. P33065, L1-5, I am wondering about this speculation. It is proven that the stronger convection happens over the regions with dry air aloft combined with the low level jet of moist air, such as Argentina and SE US. Central Africa and Amazon convection have very different convective intensity properties. Regarding the explanation of CAPE, I am wondering if there is any study to support this statement.

Rosenfeld et al. (2008) hypothesis is theoretical and, to our knowledge, has not been assessed. However, Ackerman et al. (2000) and Koren et al. (2004) demonstrated the role of carbon-based aerosols in the inhibition of convective development. The sentence has been modified as follows:

As proposed by Khaykin et al. (2013), the larger aerosol concentration in the northern tropics might reduce the Convective Available Potential Energy (CAPE). This idea was first suggested by Rosenfeld et al. (2008) who developed a conceptual model to address the question of the relationship between aerosols, cloud microphysics, and radiative properties. Their results show that at moderate cloud condensation nuclei (CCN) aerosol concentration, the CAPE is enhanced until a maximum is reached to a concentration of ~1200 cm^{-3}. Beyond this limit, larger CCN concentration has the opposite impact, preventing rainout in tropical clouds and inhibiting the convection. To our knowledge, no published study assesses this hypothesis. Nonetheless, it was demonstrated that carbon-based solar-absorbing aerosols with large optical thickness (such as soot) warm the planetary boundary layer, making it more stable and inhibiting the development of convective clouds (Ackerman et al., 2000; Koren et al., 2004).

7. P33067, L10, are you implying that the TTL could be up to 68 hPa? Or this should be said the convection impact stops at 68 hPa.

This is right, given the D-N variability and the anomaly vertical propagation, we estimate the top of the TTL somewhere between 82 and 68 hPa (corresponding to the MLS retrieval layers). More information is however needed to determine whether or not deep convections have a direct impact up to the top of the TTL. We come back to this point in the discussion, please see the response to the comment #9.

8. P33071, L5, Bottom panels shows the "anomaly" of the water vapor mixing ratio.

It is right. However the entire paragraph has been modified. Please refer to the response of the major comment number 2 of the referee #2

9. P33071, at 171, there is not much day vs. night water vapor variation in winter. Then why there is opposite day vs. night water vapor variation at 100 hPa in winter, when there is no deep convection? Could this be related to the diurnal tide? Also the amplitude of water vapor variation is very small. I worry about the error bar is greater than the signal at this level and above.

Actually, the day and night anomalies are of the same sign in winter at 177 and 100 hPa, and was attributed to the condensation-sublimation diurnal cycle related to the radiative heating rate cycle of cirrus clouds.

Nevertheless, we completed the analysis by implementing a filter based on the D-N significance. As showed in Fig. C, not all the available D-N (on a daily base) are significant. From about 50% in summer, the statistics drop to 15-25% in winter at 100 hPa. We analysed the D-Ns for which |D-N| at 177 hPa is greater or equal to 20%, which we consider as significantly convective cases. Also, we assume to be insignificantly convective cases the D-Ns for which |D-N| at 177 hPa is less than 5%. We mainly focus on strong convective tropical land areas: South America and Africa. Results for the southern tropics are showed in Figure D.

For significantly convective cases, the D-N in the UT in south tropical America and Africa is similar to that of Fig. 6a [in the final manuscript] (the larger amplitude results with the selection of the most significant cases). However, the pattern is different in the TTL. In both areas, we observe a year-long positive layer between 121 and 100 hPa, extending up to 82 hPa in summer. Another positive layer is found between 56 and 46 hPa in the LS, also similar to that of Fig. 6a [in the final manuscript].

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 [in the final manuscript]. 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.

Overall, transport by advection produces D-N in opposition of phase with respect to that of convective origin, resulting in an underestimation in the 121–100 hPa pressure range and an overestimation in the 82 – 68 hPa layer of the D-N as represented in Fig. 6a (left and middle panels in the final manuscript). Similar results are obtained in the northern tropics with less amplitude. Over oceanic areas, the D-N in the TTL is similar in amplitude and sign both for significantly and insignificantly convective cases, and presents the same characteristics than in Fig. 6b and 7b (right panels in the final manuscript).

10. P33073, why do not showing this in the main text? I think the result over the western Pacific is compensating the rest results and it should be shown as Figure 7, if not combined into Figure 6. Also, please be specific on how you define the region.

The western Pacific is now integrated in the main text so that Figures 6 and 7 [in the final manuscript] are divided in two sub-figures: a) South America and Africa and b) maritime continent and western Pacific.

References

Ackerman, A. S., Toon, O. B., Stevens, D. E., Heymsfield, A. J., Ramanathan, V., & Welton, E. J. (2000). Reduction of tropical cloudiness by soot. Science, 288(5468), 1042-1047.

Koren, I., Kaufman, Y. J., Remer, L. A., & Martins, J. V. (2004). Measurement of the effect of Amazon smoke on inhibition of cloud formation. Science, 303(5662), 1342-1345.

Livesey, N.J., and W. V. Snyder "EOS MLS retrieval processes algorithm theoretical basis." JPL Doc, D-16159/CL #04-2043 (2004).

mls.jpl.nasa.gov/data/eos_algorithm_atbd.pdf

Figures

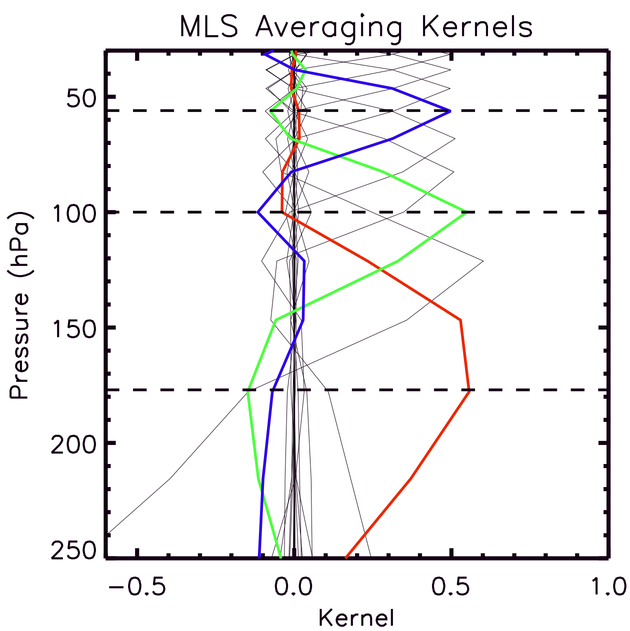

Figure A: MLS H_2O averaging kernels from 250 hPa to 30 hPa. Dashed lines represent the 177, 100 and 56 hPa levels. The red, green and blue kernels are the kernels peaking at 177, 100 and 56 hPa, respectively.

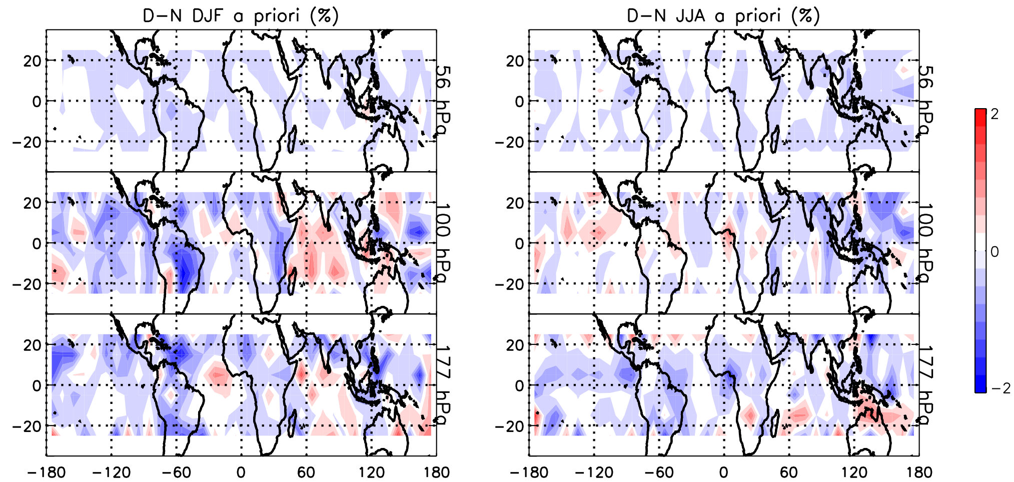

Figure B: Same as Fig. 2 (in the manuscript) but for the MLS H_2O a priori in 2012.

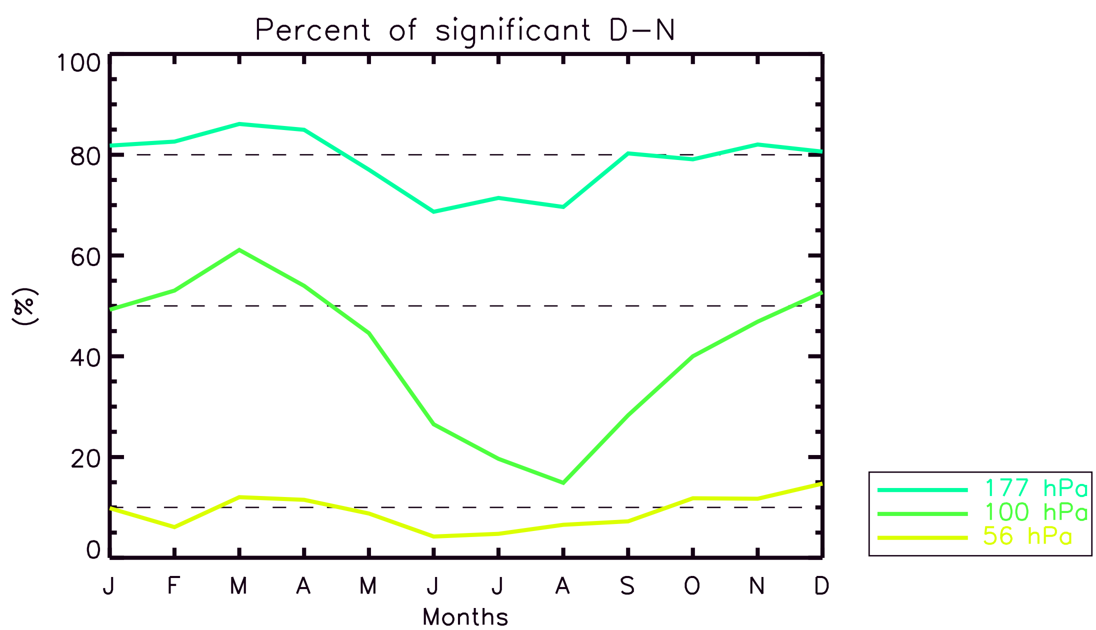

Figure C: Relative number of days in south tropical America for which the |D-N| is greater than 10% with respect to all the days when both an average daytime and night time were available (1639 days) between 2005 and 2012.

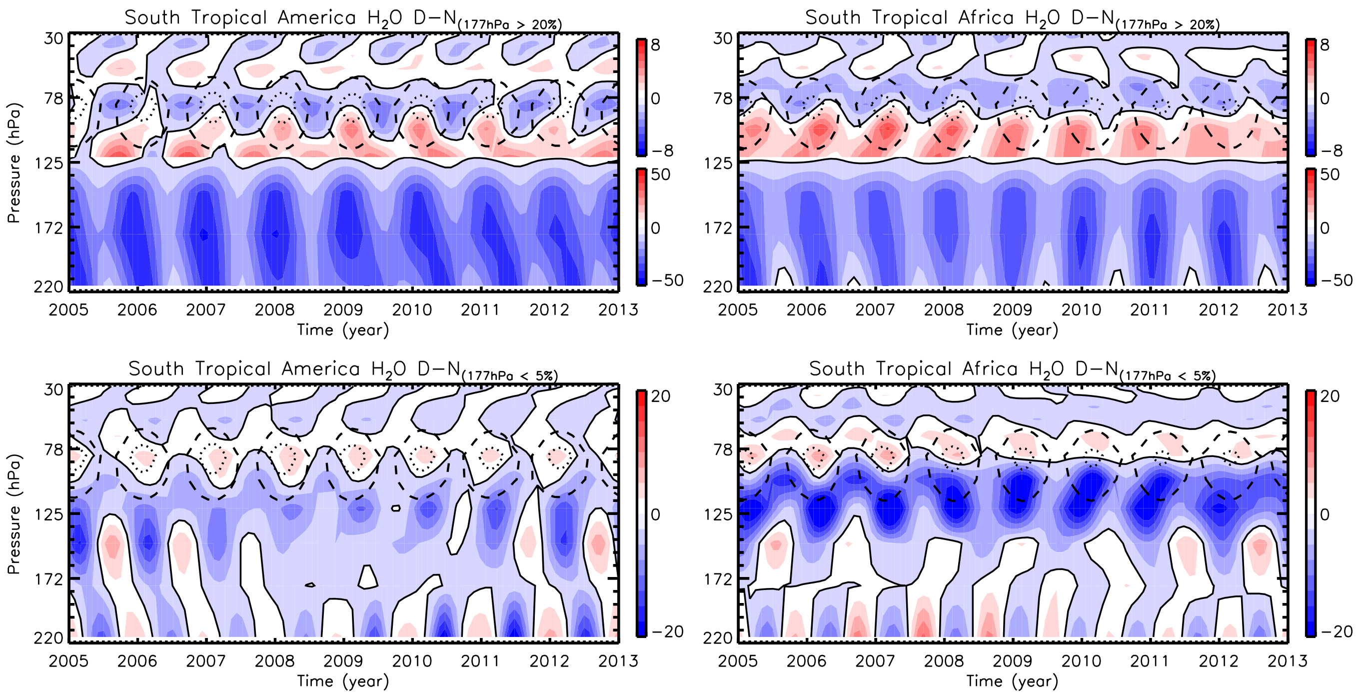

Figure D: Relative filtered H_2O D-N over south tropical South America (left) and south tropical Africa (right) considering significantly convective cases (|D-N| at 177 hPa greater than 20%) (Top) and insignificantly convective cases (|D-N| at 177 hPa less than 5%) (Bottom).

Response to Referee #2

We are grateful to the second referee whose comments helped us make a clearer analysis. His/her suggestions to estimate the impact of the a priori and averaging kernels brought, among others, further evidences that strengthen our results.

This manuscript presents an updated and refocused version of the analysis performed by Liu and Zipser (2009). The results are interesting, but the presentation is not always clear and the technical justification is incomplete in some areas. Several of the assertions in the text require additional supporting evidence, and I hope that the authors will expand their discussion to include more contextual information (e.g., how the MLS- derived diurnal cycles compare with other metrics of overshooting convection, what the results mean in a global context) – see comments below for details. Overall, the core of the study is solid and there is enough new material to justify publication. I recommend that the manuscript be reconsidered for ACP after major revisions.

Major Comments

1. Like the first referee, I have some questions regarding uncertainties and the robustness of the results at higher levels (especially at 56 hPa). The differences shown in Fig. 2 and Fig. 6 are quite small, while the MLS retrievals for each layer are somewhat dependent on the water vapour profile at other levels. This dependence on other layers can be positive (in phase) or negative (out of phase). Have you been able to confirm that the diurnal cycles at these higher levels are not artifacts of the averaging kernel dependence on the diurnal cycle at lower levels? Are there any systematic day–night differences in the a priori profiles that might propagate into the retrievals? I recommend including a discussion of these issues in the revised manuscript.

All referees have justly raised questions regarding MLS uncertainties, specifically at low-pressure levels. This study presents a picture of the difference between the daytime and the night-time H_2O content, at large scale in the whole tropics first, and in restricted areas in a second time, which, indeed deals with very small variations. In order to address this issue and assess our observations, we proceeded with a three-step analysis. First, we studied the MLS averaging kernels and showed that the averaging kernels giving the maximum information at the 177, 100 and 56 hPa levels were not only almost independent but also representative of the UT, TTL and LS, respectively. In a second time, we treated one year of H_2O a priori (2012) with the same methodology than the H_2O mixing ratio and calculated the D-N of the a priori. It resulted that although the a priori does slightly vary, its D-N is most often negative or close to zero, so that it cannot be responsible of an artificial positive signal in the H_2O mixing ratio D-N as showed in Figs. 2, 6 and 7 [in the final manuscript] above continents at 100 and 56 hPa. Finally, we estimated the percentage of days among the whole dataset for which the D-N was without ambiguity significant (limit set to 10%). We showed that the D-N is significant about 80% of the time at 177 hPa, ~50% at 100 hPa and ~10% at 56 hPa during the summertime when the convection is the strongest. For further details, please refer to the response addressed to the referee #1. As recommended, we dedicated a new section in the discussion of the revised manuscript to the analysis of the uncertainties.

2. I recommend slightly refocusing Section 3 ("Water vapour seasonal variations over land areas") to emphasize covariability in water vapour, temperature and IWC. One option would be to replace the current Figs. 4 and 5 with composite time–height seasonal cycles of (a) day–night differences (in MLS water vapour, temperature and IWC) and (b) anomalies from the climatological mean (in MLS water vapour, temperature and IWC). It might be helpful to include the western Pacific region in these plots for additional context. By relating the annual and diurnal cycles of water vapour, temperature and IWC, you may be able to make clearer arguments regarding the importance of overshooting convection relative to other TTL processes at different times of year and over different regions. This approach would allow you to replace at least the top row of plots in Figs. 6 and A1, and might enable a more detailed look at your argument regarding the effects of El Niño/La Niña.

The suggestion to emphasize the co-variability of H_2O, temperature and IWC can help to clarify our arguments. Also, we agree with the integration of the western Pacific in the main text and therefore modified Figs. 6, 7, 9 and 10 [in the final manuscript], accordingly. However, we think that the addition of the D-Ns and anomalies time-height figures of temperature and IWC would add a large volume of information that we do not consider as indispensable. We preferred another approach, which consist in integrating the annual mean daytime and night-time temperature and IWC anomalies alongside those of H_2O. This anomaly gives information on the daytime and on the night-time separately, and keeps the information on the sign and amplitude of the D-N. Figure 6 is then split in two [Figs. 9 and 10 in the final manuscript], with on the one hand the annual cycles, and on the other hand the corresponding day and night anomalies as showed in Figures E and F.

This part of the discussion has been revised as follows:

Fig. 10 shows the seasonal variations of daytime and night-time anomalies for H_2O mixing ratio and temperature over the same areas as in Fig. 9. In the UT (177 hPa), a strong night-time moistening in summer (October-March) over South America and Africa is in phase with the diurnal cycle of convection. The upper tropospheric night-time moistening is weaker above the maritime continent and nearly absent in the western Pacific. The TTL (100 hPa) in the summer is characterized by a daytime moistening above the two land convective regions, whereas anomalies show a night-time moistening in winter, and slight or insignificant night-time moistening during the whole year over the oceanic areas. The picture is very similar at 56 hPa in the LS, where daytime hydration is also observed above the two continents in the summer, and absent everywhere else where the night-time is maximum. Not shown in this figure, a daytime moistening characterises the layer near the Cold Point tropopause (centered on 82 hPa) above oceanic areas.

Temperature anomalies are more variable in the UT, characterized by a summer daytime cooling, followed by a winter daytime warming in both South America and maritime continent, and the opposite in Africa and western Pacific. The continent-oceanic dichotomy, absent in the UT, appears in the TTL. The temperature presents a year-long daytime warming (of larger amplitude in summer) over South America and Africa. However, maritime continent and western Pacific have both warming and cooling with very *little amplitude. In the LS, a daytime cooling (of larger amplitude in October-March) is shown in all areas. Only in Africa, during JJA, the daytime is warming, most likely under the influence of the underneath layer. Note that the anomaly in DJF (±0.25 K) is very consistent with the results published by Khaykin et al. (2013, Fig. 1).*

IWC anomalies (not shown in the manuscript) are characterized by a year-long positive feature in daytime (and negative in night-time) in continental areas (±0.3 mg.m^{-3}) at all levels, and the opposite in western Pacific (±0.15 mg.m^{-3}). Only the maritime continent presents both features with a positive nigh-time in December, January and April, but with a very small amplitude (mostly less than ±0.05 mg.m^{-3}).

At 100 hPa, the night-time moistening above oceanic areas during the whole year, as well as continental regions in the winter, is consistent with the negative D-N observed at the same level for insignificantly convective cases. This is attributed to a horizontal advection from neighbouring areas. In the summer, however, the continental daytime moistening during the convective season requires a hydration process. The only known mechanism compatible for hydrating this layer is the convective overshooting of ice crystals, sublimating in the next day until the next cycle of convection.

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. H_2O 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.

I cannot identify these ENSO effects in the current figures (see minor comment below); perhaps showing difference plots relative to the composite annual cycle would highlight the differences you are reporting? Relative to the current manuscript, this change would eliminate the annual cycle in water vapour (shown many times previously) and the interannual variability (only currently used with respect to the impact of ENSO phase).

In order to highlight the perturbation in the D-N linked to ENSO, we computed the D-N yearly average. Figure G shows the yearly averaged D-N at 177 and 100 hPa for (top row, from left to right) North tropical America, Africa, maritime continent and western Pacific, and (bottom row) their southern counterparts. The most striking impact of ENSOs is in South tropical America where the mean D-N in the UT (TTL) drops (rise) after the 06-07 event and rises (drops) again only after the 09-10 event. The South tropical maritime continent follows an almost similar pattern while South tropical Africa and Western Pacific show the opposite. The ENSO effect in the northern tropic is not as much apparent as in the southern but roughly seems to show an opposite variation, except for western Pacific.

Fig. G will not be added in the manuscript but the paragraph p33068, l7-25 has been rephrased as follows:

The El Niño and La Niña events do not appear in the Figs. 6 and 7 (a and b) because the FFT filter removes inter-annual variations. However, by influencing the tropical circulation, these events indirectly perturb the D-N and anomaly amplitudes. The ENSO events of 2006-07 and 2009-10 (Su and Jiang, 2013) match both the upper tropospheric (TTL) strengthening (weakening) followed by the weakening (reinforcing) of both D-N and anomaly amplitudes over south tropical South America and maritime continent, as well as the opposite effect above south tropical Africa and western Pacific.

The ENSO 2009-10 was the strongest, displaying the warmest sea surface temperatures in the Pacific since 1980, followed by a strong La Niña event the next summer (Lee and McPhaden, 2010; Kim et al., 2011). As shown by Su and Jiang (2013), the ENSO 2006-07, (an Eastern Pacific event), resulted in a weakening of the Walker circulation, while the stronger ENSO 2009-10, (a central Pacific event), resulted in an eastward displacement of the Walker cell and a strengthening of the Hadley cell. The authors found a 5% increase of high cirrus clouds (at 100 hPa) in South America along with a 30% drop above the Pacific in 2009-10. Amplitude changes in H_2O *D-N and anomalies in the southern tropics (Figs. 6 a and b) are consistent with the Su and Jiang (2013) observations during the El Niño events, further underlying the convective origin of water vapour variations in the TTL and in the stratosphere. In the northern tropics (Figs. 7a and b), these modulations are approximately out-of-phase with respect to the southern tropics; yet, they do not coincide as much as in the south to the ESNO years, meaning that other perturbations probably affect the convection.*

3. I would like to see more in the discussion regarding how seasonal changes in the diurnal cycle of UT/TTL water vapour relate to seasonal changes in the properties of convection (particularly overshooting convection) based on previously published work (e.g., TRMM, CloudSat, etc.), as well as what (if anything) the results imply for the importance of overshooting convection to global stratospheric humidity.

As suggested, we introduced studies based on TRMM and CloudSat-CALIPSO that show good agreement with the results presented in our study. The following paragraph has been added in the discussion.

The seasonal changes in the H_2O *D-N (i.e., summertime maximum amplitude, negative in the UT, positive in the TTL and LS) closely follow the distribution of overshooting convection seasonal cycle as measured from the Tropical Rainfall Measuring Mission (TRMM) (Liu and Zipser, 2005). The authors showed that in DJF (JJA), OPFs were essentially found between 0 and 20°S (0 and 20°N), while March-May and September-November are transition periods during which the convective systems move from South to North and conversely, so that the maximum of convection is found at the equator. Also, Iwasaki et al. (2010) confirmed that the overshoot samples are not rare at the tropical belt scale, and induce a potential impact on the stratospheric hydration. The number of events penetrating the 380-K potential temperature level in the TTL, as measured by CALIPSO, is approximately* 7.10^6 *events per year in the tropical belt (20°N-20°S). A hydration of about 100 tons of* H_2O *per event was calculated using a combination of CloutSat and CALIOP data. Their results showed more cases during the day than during the night, and more cases over land than over the ocean. No discussion is made about the impact of the time of overpass, which may alter the statistics in some regions, but the results are qualitatively in agreement and compatible with this study.*

4. The text of the manuscript requires substantial editing. In particular, there are a number of sentences that could be reworded or split to improve clarity and readability. It may be helpful to engage the services of a professional editing service prior to submitting a revised manuscript.

Several persons of competence have edited the manuscript that we believe to be now of high English standard.

Minor Comments

1) p.33057, l.7-8 : Sherwood (2000) showed that vertical motion derived from sounding data over the "stratospheric fountain" region is actually downward; see also Hartmann et al. (2001) for an explanation of how radiative cooling can exist at the tropopause in this region despite cold temperatures.

It is right, both Sherwood and Hartmann demonstrate the subsidence of air masses near convective centers. But when the air mass is no more cooled by the underlying anvil, the upward dynamic prevail anew. Nevertheless, the sentence has been rephrased as follows:

The long known convective area in the Western Pacific, referred to as 'stratospheric fountain' (Newell and Gould-Stewart, 1981), has been the focus of numerous field campaigns.

2) p.33057, l.25-26 : If possible, you should refer back to the TROPICO campaign in the discussion or conclusions. How has this study helped to inform or provide a baseline for TROPICO?

The following paragraph has been added to the conclusion:

TRO-pico's objectives are to evaluate to what extent the overshooting convection and involved processes contribute to the stratospheric water vapour entry. Light and medium size balloons were launched as part of two field campaigns (2012 and 2013) held during the convective period in Bauru, Sao Paulo state, Brazil. Flights carrying Pico-SDLA (Durry et al., 2008) and Flash-B (Yushkov et al., 1998) hygrometers were launched early morning and late evening while radiosondes were launched up to 4 times a day during the most convective period. The measurements, still under analysis, are matched with space-borne and model data. Then, to evaluate the local results obtained in Bauru with respect to larger scale, comparisons with climatologies will be necessary. Although seasonal and annual variation of H_2O *has been extensively studied, few studies were devoted to the geographical and temporal variability of its diurnal cycle in the TTL. With this study, we aim to deliver a comprehensible landmark for TRO-pico as well as future research debating the impact on* H_2O *of the continental tropical convection.*

3) p.33058, l.3 : I'm not sure that I would say that water vapour is a "source of" photochemical reactions – it's a source of OH and a key player in stratospheric photochemistry.

It has been rephrased as follows:

Being the most powerful greenhouse gas and playing an important role in the UT, TTL and LS chemistry as one of the main sources of OH radicals, […]

4) p.33058, l.13-14 : The wording of the beginning of this sentence ("If the process is well-captured by cloud-resolving models") is confusing. I think that you mean "Although this process is well-captured in cloud-resolving models" – is this correct?

It is correct, the sentence has been corrected.

5) p.33061, l.2-4 : How different is this qualitative definition of the TTL from the definition based on MLS pressure levels? The locations of the LZRH and CP change by region – are the results in any of the study regions sensitive to the definition of the TTL?

There is no major difference between the MLS pressure-based and the qualitative definition, nor are our results sensitive to it. Nonetheless, a comprehensive definition of the pressure range that we consider to be the TTL is needed for the clarity of the study.

6) p.33061, l.8 : AURA is not an acronym – it should be replaced with Aura.

It has been corrected.

7) p.33061, l.15 : The wording of this sentence is difficult to follow. Is it that the precision varies from 40% at 220 hPa to 6% at 31 hPa and the accuracy ranges from 25% at 220 hPa to 4% at 31 hPa. Should these values be preceded by ±?

The sentence has been replaced by:

The precision ranges from 40% at 215 hPa to 6% at 46 hPa, and the accuracy from 25% at 215 hPa to 4% at 46 hPa, for a vertical resolution of 2.5-to-3.2 km.

8) p.33061, l.23 : v3.3 is biased relative to v2.2 – does this bias represent an improvement in MLS estimates of IWC? Is it clear at this point which version is more accurate?

We compared both versions and no significant difference was observed in the D-N at 177 and 100 hPa.

9) p.33063, l.4-5 : The 100 hPa day–night differences only appear to be out of phase with the 177 hPa differences over portions of south tropical South America and south tropical Africa, and over Africa the region that is out of phase doesn't line up with the largest signal at 177 hPa. Over other regions (and during JJA), the variations seem to be small or in phase with the UT.

It is right. Variations in-phase or out of phase but not lining up with the maximum D-N amplitude at 177 hPa are the result of competing possesses: 1) a D-N variability induced by the convection (e.g. negative in the UT and positive in the TTL), and 2) a variability largely impacted by horizontal transport (negative in the lower TTL and positive around 80 hPa, similar to what is observed above oceanic areas). Figures 6 and 7 [in the final manuscript] result then from the average of very convective days when the first case is predominant and days when the convection is weak or inexistent, giving weight to the second case. Figure D [please refer to response to referee #1] shows the D-N for the most convective days only (when the |D-N| at 177 hPa is greater than 20%) compared to non-convective days (|D-N| at 177 hPa less than 5%). In the case of the most convective days, the D-N sign present a clear opposition of phase between UT and TTL with a good alignment with respect to the maximum amplitude at 177 hPa.

10) p.33063, l.11-14 : Are relative humidities sufficiently high at 56 hPa in this region to support a diurnal cycle in thin cirrus / sublimation?

This argument has been removed from section 2.2. The origin of the positive D-N observed above continental regions in the LS is now discussed in the section 4.3 of the discussion (see response to major comment 2). It is attributed to the temperature variability induced by convection, although it is possible that the information captured by the kernel peaking at 56 hPa comes from the 70-60 hPa region, where the temperature is colder than at 56 hPa.

11) p.33064, l.17-19 : Is the amplitude of the diurnal cycle in temperature quantitatively consistent with the diurnal variation of H_2O, or only qualitatively? More specifically, can the amplitude of the diurnal cycle in temperature fully account for the amplitude of the diurnal cycle in water vapour? Does the MLS temperature data agree with COSMIC in sign / magnitude?

As already mentioned, MLS does not sample the atmosphere at the maximum of convection, and then cannot estimate the maximum of the diurnal amplitude of temperature. Nonetheless, at 01:30 and 13:30 LT the MLS night-time and daytime temperature anomalies (Fig. E) are of ±0.25 K, positive at night and negative at day, which is very consistent with the COSMIC data in magnitude and sign (about ±0.2 K, Khaykin et al., 2013).

L17-19 have been rephrased as follows:

Khaykin et al. (2013) estimated the temperature diurnal cycle from the COSMIC satellites GPS Radio Occultation measurements. At the MLS sampling time, the temperature measured by COSMIC had not reached its maximal amplitude but did show its premises, with a ~0.2 K cooling (warming) at 13:30 LT (01:30 LT), in agreement both in sign and magnitude with the temperature measured by MLS. At 100 hPa, the COSMIC temperature diurnal cycle is consistent with the positive continental signature of H_2O *D-N in contrast to oceanic areas where the D-N is insignificant.*

12) p.33064, l.21 : Does "such event" refer to the diurnal cycle of COSMIC temperature? Please clarify.

The sentence has been modified as follows:

In JJA in the northern tropics, late afternoon cooling is limited to Central Africa and does not appear elsewhere.

13) p.33066, l.19 : The vertical location of the hygropause appears to vary substantially by season.

It has been modified as follows:

The driest hygropause is observed from January to May at about 80 hPa in the four regions.

14) p.33067, l.8-10 : It's difficult to tell from the figure whether the vertical propagation of the TTL summer maximum is any faster than the vertical propagation of the TTL winter minimum (also, shouldn't these be "winter maximum" and "summer minimum" since Fig. 4 shows the southern hemisphere?).

The confusing sentence has been removed.

15) p.33067, l.23 : "6% weaker"; "3% weaker" – are these relative or absolute differences? Specifying the amplitude or maxima/minima (e.g., "xx% relative to yy% in the southern hemisphere") may help to avoid confusion here.

We agree with the referee and replaced l.23 and l.27 by:

However, the D-N features (middle panels Figs. 7a and b) are significantly different: in the UT, a weaker *night-time maximum humidity is displayed (-17% relative to -25% in the southern tropics), and in the TTL, above South America and Africa, a weaker daytime maximum is displayed (1.5% relative to 4% in the southern tropics).*

[…]

The monthly mean anomalies are similar to those of the SH, although of lesser amplitude in the UT (±8-18% relative to ±18-28% in the southern tropic).

16) p.33068, l.4-25 : I can't clearly identify the weakening/strengthening of the amplitude in the UT/TTL that is supposed to be related to ENSO in these figures. It looks like the amplitude in the TTL strengthens in both 2008–2009 and 2009–2010, while the amplitude in the UT weakens in both years. . .

Please refer to the response of the major comment number 2.

17) p.33069, l.10 : No sign of diurnal variation in what? Water vapor? Tropopause temperature/vertical location? Please clarify.

The paragraph has been modified as follows:

As explained in section 2.4 and also suggested by Danielsen (1982), the late afternoon cooling by injection of adiabatic cooled air from overshooting convective systems is a well-understood feature which may have two implications: 1) drying by condensation at temperatures below saturation either at, or below, the Cold Point tropopause (Danielsen, 1982; Sherwood and Dessler, 2001), and/or 2) moistening by the subsequent sublimation of ice crystals injected in the TTL by overshooting convection. The first option would explain the positive D-N signal in the extremely dry tropopause region above the maritime continent and western Pacific. This results from the heating rate cycle of cirrus clouds formed by condensation because of the low temperature (Hartmann et al., 2001; Corti et al., 2006). However, the wetter TTL in continental areas requires a hydrating process that the first scheme does not provide.

18) p.33069, l.19-22 : I don't follow the two implications here. My understanding is that the two possible effects should be (1) drying by condensation occurring because of the relatively low temperatures in cold overshooting air, or (2) moistening by the subsequent sublimation of ice crystals injected by overshooting convection.

This point is also answered in the previous point.

19) p.33070, l.12-13 : Does a greater efficiency of moistening necessarily mean more intense convection? How does the background RH compare among these regions? By many measures (lightning, radar reflectivity), convection over south tropical Africa is more intense than convection over south tropical

South America, especially during DJF (e.g., Petersen and Rutledge, 2001). If the amplitude of the diurnal cycle in water vapour is entirely attributable to the intensity of overshooting convection, how is this consistent with the amplitude being greater over south tropical South America than over south tropical Africa?

Our observations are consistent with the Yang and Slingo (2000) mean brightness temperature (BT) climatology. They show that the mean BT are 1) lowest in DJF in the southern tropic with respect to the northern tropic in JJA, and 2) South America presents lower BT (in DJF) than Africa. Also note that in the northern tropic in JJA, Africa has lower BT than South America.

Regarding the relative humidity (RH), the Gettelman et al., 2006, climatology shows that, at least in the UT, the RH is similar (~ 60-70%) in the northern and southern tropics in JJA and DJF, respectively, in the areas of interest of this study.

A more efficient convection would lead to a wetter UT in convective season and consequently larger gradient in the monthly mean anomaly. South tropical America UT anomaly amplitude is indeed greater than in south tropical Africa and, although weaker than in the south, north tropical Africa anomaly amplitude is greater than north tropical Americas', in agreement with Yang and Slingo (2000) BTs.

We agree that a larger sampling would result in a better characterization of the impact of convection, but the fact that MLS samples the different tropical regions at the same local time already allows drawing conclusions.

The paragraph has been modified as follows:

The H_2O mixing ratio, D-N, and anomalies show marked seasonal variations in the eight regions. However, the upper tropospheric D-Ns are of systematically larger amplitude above land areas, particularly in the southern tropics. Another typical feature of these areas is the positive D-N at the bottom of the TTL and up to 82 hPa during the most convective season, in contrast to oceanic areas that display a positive D-N near the tropopause at 82 hPa.

The main differences between these areas are their convection characteristics, with late afternoon maximum intensity over tropical land and weak diurnal change over ocean. Moreover, the stronger signal in the south tropical summer, particularly above South America, indicates a much more intense convection than in the northern tropics. These observations are consistent with the Yang and Slingo (2000) mean brightness temperature climatology showing the lowest brightness temperatures, synonymous of colder cloud top, in the southern tropics in DJF and more precisely over South America. Also, this North-South difference in D-N amplitude cannot be, at least in the UT, attributed to a gradient in the relative humidity (RH). In South America, Africa, maritime continent and western Pacific, north and south tropical RHs are comparable during their respective summer (Gettelman et al., 2006).

In the TTL and LS, the variability of the anomaly in all areas, which remains unchanged regardless of the strength of the convection in the UT, is consistent with the seasonal variability of the Cold Point temperature. This indicates that in the TTL and above, the continental convection does not affect H_2O seasonal variability, even though, it strongly impacts its diurnal cycle.

20) p.33070, l.16–18 : What do these results mean, if anything, regarding the global impact of deep continental convection in the TTL/LS? For instance, Fig. 6 suggests that the amplitude of the diurnal cycle over the convective regions is very small (less than 5%) relative to the amplitude of the typical seasonal cycle in the TTL/LS; on the other hand, MLS may substantially underrepresent the diurnal cycle in water vapour at these levels (cf. Fig. 1). Do you feel comfortable making any statements about this at this point?

As it is rightly underlined, for many aspects, MLS underestimates the H_2O variability at all levels because not in phase with its largest magnitude. This is the reason why we adopted a quantitative approach and try to determine the nature of the involved processes (hydrating or dehydration), their origins and mechanisms, and not how much water is injected or removed from a given layer. MLS samplings offer what we could define as an initial and a final state (before/after convection) of H_2O, so we can only hypothesize how it evolved in-between. However, our analyses gather enough clues to present reliable conclusions.

21) p.33071, l.18-21 : Is there any indication from previous work that ice crystals from overshooting convection can moisten the atmosphere at 56 hPa? At the very least, it needs to be shown that these diurnal cycles are not artifacts of the retrieval (e.g., averaging kernel, a priori profiles, covariability with temperature).

Please refer to responses to major comments 1 and 2.

22) p.33072, l.15-19 : This argument regarding the diurnal cycle of water vapour at 56 hPa over the Asian monsoon region requires further discussion and support. Is there any published evidence of cirrus clouds at this altitude (e.g., SAGE II, CALIPSO)?

Asian and Central American monsoon regions are at the edge of the tropics and characterized by complex convective systems of different origins and characteristics relative to those occurring deeper in the tropics and analyzed in the present study. The convective aspects of the monsoon, especially the Asian one, has been extensively studied, and although the methodology developed in our study is applicable to those regions, it would require a whole new analysis that could be developed in a different paper.

In order to clarify the observations relative to monsoon regions, the following paragraph has been added to the discussion:

In the Asian and Central American monsoon regions, we noticed at 56 hPa a positive D-N signal in JJA, in absence of strong night-time moistening in the UT. This atypical feature potentially results from the influence of the adjacent seas; namely, Gulf of Mexico and Caribbean Sea for the Central America monsoon region, and South China Sea and Bay of Bengal for the Asian monsoon region. Yang and Slingo (2000) showed that in these regions, both brightness temperature and precipitation diurnal cycle are *shifted by about 10-12 hours from sea to land with a sharp transition. Since we average H_2O in a 10˚x10˚ grid, both land and ocean are combined in these areas, resulting in a composite land-ocean convection cycle, which explains the absence of a strong signal in the UT. Unlike the maritime continent where land and ocean are also combined, Asian and Central America monsoon regions present the continental convection signature in the LS (e.g. positive D-N). Although the methodology developed in our study is applicable to monsoon regions, it would require a dedicated analysis beyond the scope of this study.*

23) p.33072, l.25 : Should "daytime" at the end of this line be "nighttime"?

The paragraph has been replaced by:

The convective origin of the TTL and LS hydration is confirmed by the humidity and temperature daytime and night-time seasonal variations over the various land tropical regions. The TTL daytime moistening by sublimation of up-drafted ice crystals up to 82 hPa, and the LS daytime moistening associated to the temperature cycle induced by convection, are characteristics of summertime south tropical land. Similar patterns, but of lesser intensity, are found in north tropical land, suggesting that convective overshoots are less frequent or less vigorous in the northern tropics. In comparison, oceanic locations present a daytime maximum water vapour at the tropopause level consistent with the cirrus daily cycle of radiative heating origin.

24) p.33073, l.5-16 : As mentioned above, I recommend integrating this appendix with the main text of the manuscript.

We integrated the western Pacific to the main text.

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Figures

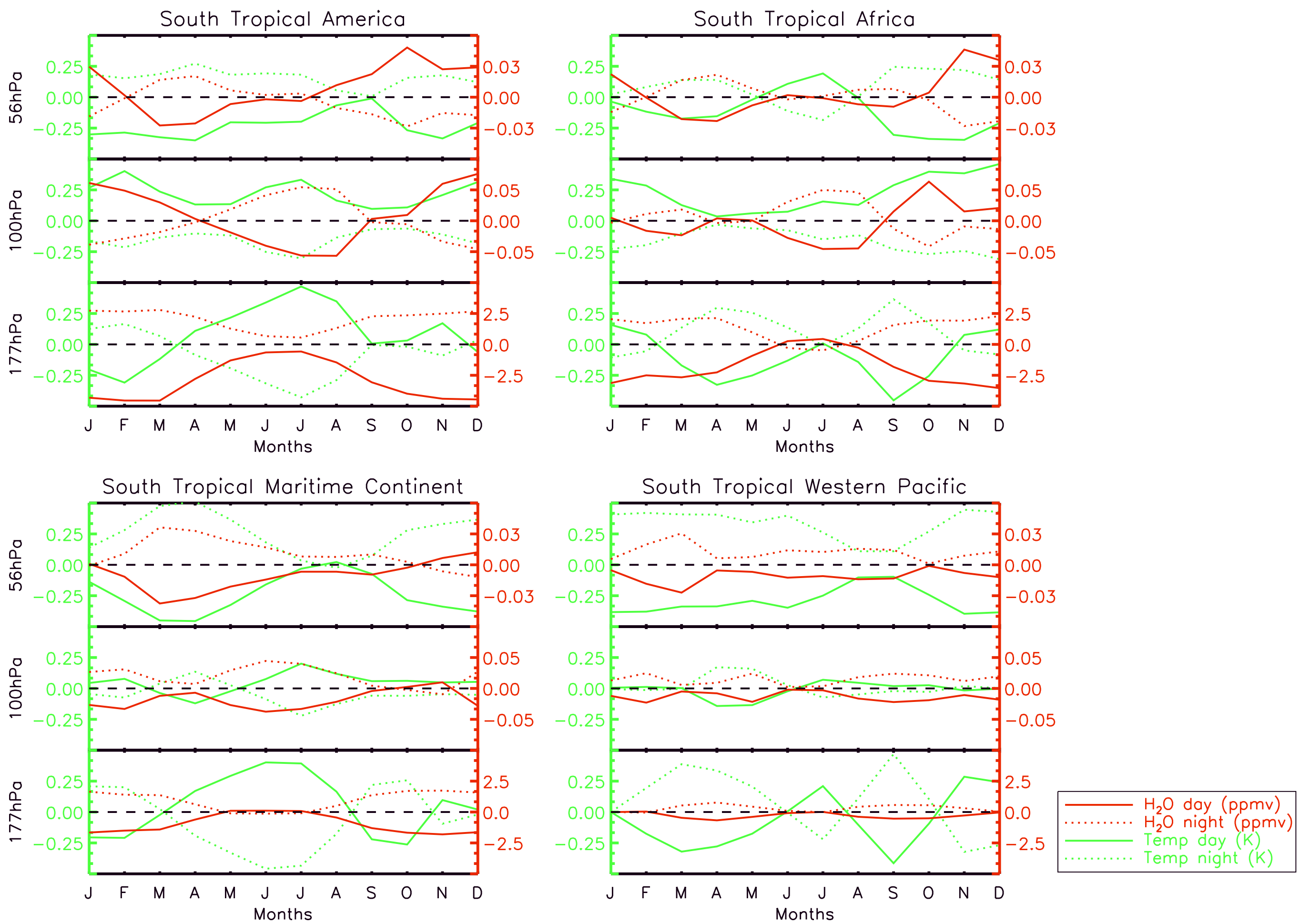

Figure E. Monthly daytime H_2O (red solid line), night-time H_2O (red dotted line), daytime temperature (green solid line) and night-time temperature (green dotted line) anomalies, calculated for each month as the difference between the monthly average daytime (night-time) and the monthly average, for the 2005-2012 period, at 177, 100 and 56 hPa in South tropical America (top left) and South tropical Africa (top right), South tropical maritime continent (bottom left) and South tropical western Pacific (bottom right).

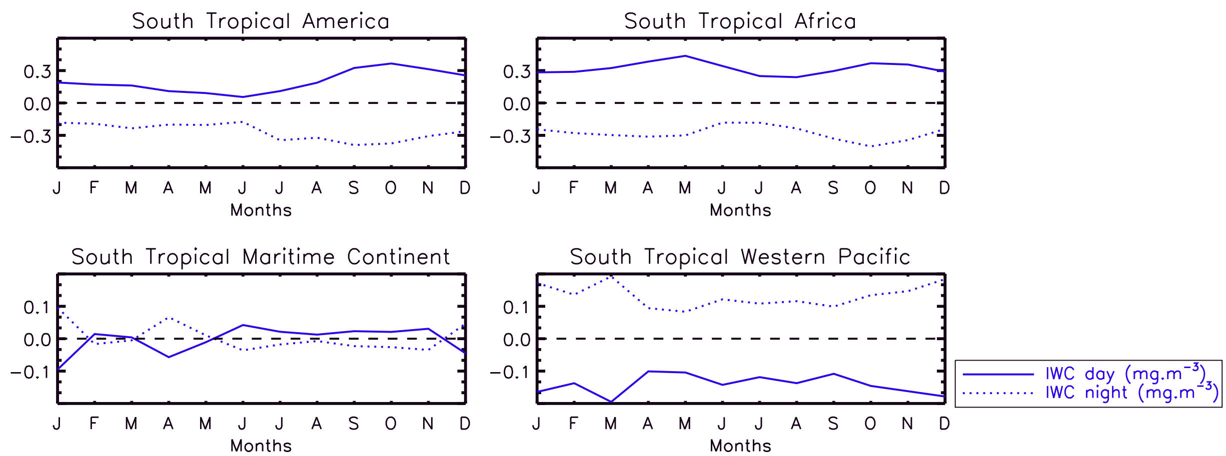

Figure F. Same as Fig. 1 but for IWC at 100 hPa.

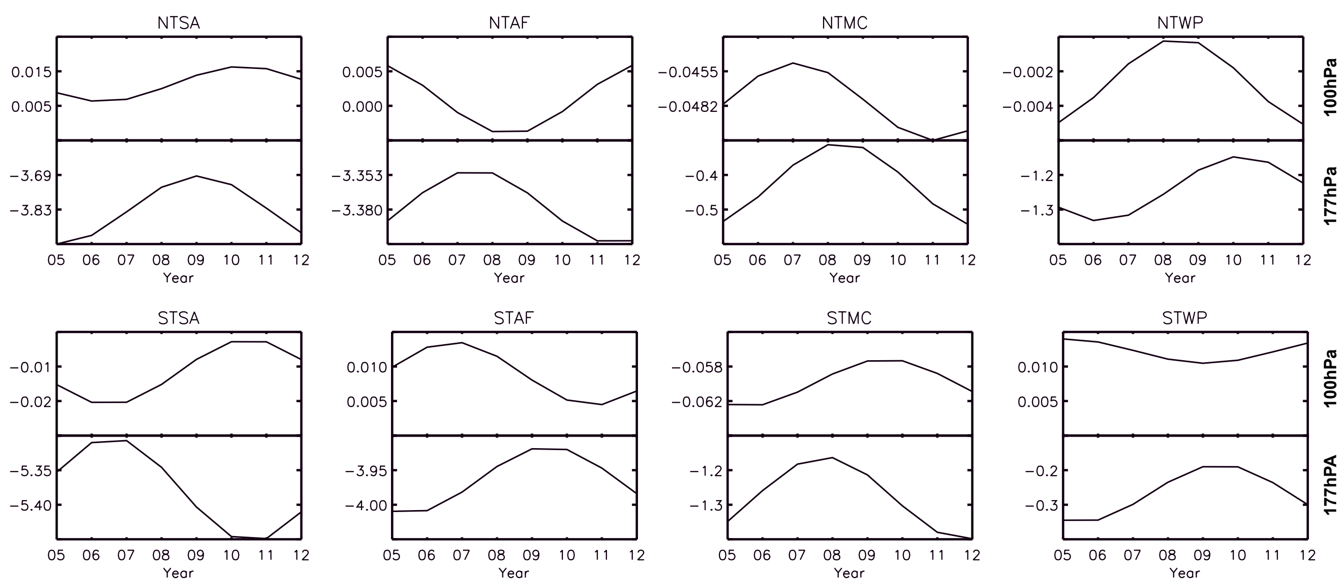

Figure G. (Top) Yearly average in ppmv of the filtered D-N at 177 and 100 hPa above (from left to right) North tropical America, Africa, maritime continent and western Pacific. (Bottom) Same as top but for South tropical America, Africa, maritime continent and western Pacific.

Response to Referee #3

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.

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In general, this paper focused on an important topic and the results are interesting. However, as detailed below, there are a number of major issues of this study, which needed to be addressed before it can be considered for publication in ACP. I recommend rejection of this paper in present form but encourage resubmission, to allow sufficient time for the authors to address these issues.

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, which cannot be reduced by averaging.

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.

(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).

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.

(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.

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 H_2O 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) showing up 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 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 variability of H_2O 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.

(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].

p.33066 l.19-22 has been rephrased to clarify this point:

In the LS, H_2O 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.

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.

We agree with the referee that the seasonal H_2O variation at the tropopause level and above is modulated by the temperature and large-scale transport. However, the diurnal cycle of H_2O 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 H_2O (whether the H_2O background at 56 hPa origins from the underneath layers or has been transported from the other hemisphere) but modulates the in situ 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. H_2O 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.

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.

It is true that on a zonal average, H_2O 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, sub-tropical, 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 (e.g. Figure D, response to referee #1). Furthermore, the UT anomaly at regional scale is significantly stronger above south tropical land than above north tropical land.

(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.

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

Minor Comments:

In addition to the places already pointed out by referees 1 and 2, I have a few other 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.

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

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

True, it has been modified.

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

The screening method is called "2σ-3σ method" and consists in an iterative computation of the mean IWC for 10° latitude band rejecting value greater than 2σ followed by the selection of all IWC measurements greater than this mean + 3σ. 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).

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

True, it has been modified.

(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.

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

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

Please refer to major comment 1.

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

Hemisphere has been changed into tropics.

(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).

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

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

We modified the wording as suggested.

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

We modified the wording as suggested.

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

We modified the wording as suggested.

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

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

Overall, this paper studied a very important topic. However, it needs more work to make it appropriate for publication in ACP.

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.

Liu, C., and E. J. Zipser (2009), Implications of the day versus night differences of water vapor, carbon monoxide, and thin cloud observations near the tropical tropopause, J. Geophys. Res., 114, D09303, doi:10.1029/2008JD011524.

D. L. Wu, J. H. Jiang, W. G. Read, R. T. Austin, C. P. David, A. Lambert, G. L. Stephens, D. G. Vane, and J. W. Waters. Validation of Aura MLS cloud Ice Water Content (IWC) measurements. J. Geophys. Res., 113:D15S10, doi:10.1029/2007LD008931, 2008.

Relevant changes in the manuscript

Regarding the entire manuscript, we integrated results and discussions from the western Pacific region in the figures and main text (this region was previously in the appendix).

Numerous sentences in the manuscript have been rephrased or split to improve the clarity of the text and meet the APC high standard.

Below is a list of specific changes:

- P2 l2-7, the conclusions regarding H_2O variability in the LS has been refined in the abstract.
- P7-8, we added two paragraphs to the section "2.2 Tropical Water Vapour" :
    - P7 l27-31 and P8 l1-8, a new paragraph is dedicated to the analysis of MLS H_2O averaging kernels.
    - P8 l9-20, a new paragraph is dedicated to the analysis of MLS H_2O a priori.
- P9 l26-32 and P10 l1-5, we further detail the possible role of aerosols in the inhibition of convective processes.
- P12-18, the discussion has been divided into 3 sections:
    - P13 l3-32 and P14 l1-2, in the new section "4.1 Uncertainties" we demonstrate robustness of our analysis in term of uncertainties.
    - P14 l4-30, the new section "4.2 Convective versus non-convective scenarios" is dedicated to the comparison between significantly and insignificantly convective days.
    - P15-18, section "4.3 Hydrating-dehydrating processes" is based on the former discussion but new paragraphs have been added.
        - P17 l16-27, the paragraph is dedicated to the H_2O variability in the LS. The conclusions are refined with respect to the previous version of the manuscript.
        - P17 l28-32, in a new paragraph we discuss the observed D-N in monsoon regions.
        - P18 l9-23, in a new paragraph we discuss the results of previous studies using TRMM and CALIPSO.

- P18 l25-32 and P19 l1-5, a new paragraph in the conclusion develops the relation between this study and the TRO-pico project.

- P19 l26-30, our conclusion regarding the H2O variability in the LS has been refined.

- P30, Table 1 is new.

- P31, Figure 1 has been updated.

- P32, Figure 2 has been updated. We added the western Pacific boxes on the top right panel.

- P33, Figure 3 is new.

- P34, Figure 4 is new.

- P36-37, Figures 6a and b have been updated. We separated land (a) and ocean (b) and added the western Pacific.

- P38-39, Figures 7a and b have been updated. We separated land (a) and ocean (b) and added the western Pacific.

- P40, Figure 8 is new.

- P41, Figure 9 has been updated. We added the western Pacific.

- P42, Figure 10 is new. We added the western Pacific. The temperature day and night anomalies are also showed.