

This discussion paper is/has been under review for the journal Atmospheric Chemistry and Physics (ACP). Please refer to the corresponding final paper in ACP if available.

Impact of tropical land convection on the water vapour budget in the Tropical Tropopause Layer

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Received: 18 November 2013 – Accepted: 2 December 2013 – Published: 18 December 2013

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Published by Copernicus Publications on behalf of the European Geosciences Union.

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Abstract

The tropical deep overshooting convection is known to be most intense above continental areas such as South America, Africa and the maritime continent. However, its impact on the Tropical Tropopause Layer (TTL) at global scale remains debated. In our analysis, we use the 8 yr Microwave Limb Sounder (MLS) water vapour (H₂O), cloud ice water content (IWC) and temperature datasets from 2005 to date, to highlight the interplays between these parameters and their role in the water vapour variability in the TTL, separately in the northern and southern tropics. The water vapour concentration is displaying a systematic diurnal cycle with a night-time peak in the tropical Upper Troposphere (pressure ≥ 146 hPa) and the opposite in the TTL (121 to 68 hPa) and the tropical Lower Stratosphere (pressure ≤ 56 hPa), of larger amplitude above continents than continental-oceanic areas such as the maritime continent or full oceanic areas such as the Western Pacific. In addition, the amplitude of the diurnal cycle is found systematically larger (5–10 %) in the southern than in the northern tropics during their respective summer, indicative of a more vigorous convective intensity in the south. Using a regional scale approach, we investigate the geographical variations of mechanisms linked to the H₂O variability. In summary, the MLS water vapour, ice water cloud and temperature observations are demonstrating a clear contribution of TTL and lower stratosphere moistening by ice crystals overshooting updrafts over land tropical regions and the much greater efficiency of the process in the Southern Hemisphere.

1 Introduction

The Tropical Tropopause Layer (TTL), the transition layer sharing Upper Tropospheric (UT) and Lower Stratospheric (LS) characteristics, is the gateway for Troposphere to Stratosphere Transport (TST), and plays a key role in the global composition and circulation of the stratosphere (Holton et al., 1995; Fueglistaler et al., 2009). TST processes responsible for the upward motion of air masses are: (1) the slow ascent

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13, 33055–33087, 2013

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(300 m month⁻¹) due to radiative heating associated with horizontal advection and known as “Cold Trap” (Holton and Gettelman, 2001; Gettelman et al., 2002; Fueglistaler et al., 2004), (2) fast overshooting updrafts followed by detrainment referred as “Freeze and Dry” process (Brewer, 1949; Sherwood and Dessler, 2000, 2001, 2003; Dessler, 2002), and (3) the fast and direct injection by “geyser-like” overshoots (Knollenberg et al., 1993; Corti et al., 2008; Khaykin et al., 2009) that can penetrate into the LS. The long known convective area surmounted by slow radiative ascent in the Western Pacific referred as “stratospheric fountain” (Newell and Gould-Stewart, 1981) has been the location of numerous field campaigns. However, studies in the early 2000s pointed out that most vigorous convection occurs over continental tropical areas where overshooting precipitation features (OPFs) are more frequent (Alcala and Dessler, 2002; Liu and Zipser, 2005) with a marked diurnal cycle and a pronounced late afternoon maximum (Liu and Zipser, 2005) in contrast to oceanic regions of little diurnal variation. Evidence of TTL-penetrating overshooting continental convection and its impact on trace gases, aerosols, water vapour, ice particles, chemical composition and transport mechanisms were raised during the HIBISCUS, SCOUT-O3, SCOUT-AMMA and TROCCINOX field campaigns in South America, West Africa and Australia between 2001 and 2006 (Corti et al., 2008; Schiller et al., 2009; Cairo et al., 2010; Pommereau et al., 2011). A significant contribution of continental convection to the chemical composition of the LS has been reported by Ricaud et al. (2007, 2009) from ODIN-SMR satellite observations, showing higher concentration of tropospheric trace gases (N₂O and CH₄) in the TTL during the southern summer, consistent with the cleansing of the aerosols in the LS seen by CALIPSO during the same season (Vernier et al., 2011).

The present study deals with one of the most debated aspect of the TTL and the LS, the budget of water vapour (H₂O), and aspires to be a baseline for further studies related to the TROPICO project (www.univ-reims.fr/TRO-pico). TROPICO aims to monitor H₂O variations in the TTL and the LS linked to deep overshooting convection during field campaigns, which took place in the austral summer in Bauru, Sao Paulo

state, Brazil, involving a combination of balloon-borne, ground-based and space-borne observations and modelling.

Being the most powerful greenhouse gas and the source of several important photochemical reactions, H₂O is a key parameter in the radiative balance and chemistry of the stratosphere and its variation can affect climate (Solomon et al., 2010). The mean tropical (20° N–20° S) H₂O concentration is estimated between 3.5 and 4 ppmv in the TTL (at 100 hPa) (Russell et al., 1993; Weinstock et al., 1995; Read et al., 2004; Fueglistaler et al., 2009). In agreement with this mean concentration, Liang et al. (2011) estimated a mean H₂O stratospheric entry of 3.9 ± 0.3 ppmv at 100 hPa in the tropics.

Although the moistening of the lower stratosphere by convective overshooting is well demonstrated, its contribution at global scale is still debated. As an example, in 2006, the SCOUT-AMMA campaign in Western Africa revealed a 1 to 3 ppmv (with a 7 ppmv peak) moistening of the 100–80 hPa layer (Khaykin et al., 2009). If the process is well captured by cloud resolving models (Chaboureau et al., 2007; Jensen et al., 2007; Grosvenor et al., 2007; Chemel et al., 2009; Liu et al., 2010; Hassim and Lane, 2010), global scale models do not integrate this kind of sub-grid scale non-hydrostatic process yet, which may result in an underestimation of the impact of overshoots at large scale. A better knowledge of the hydration-dehydration processes in the TTL and the LS, is thus primordial to understand the long-term evolution of stratospheric H₂O, known to have increased by an average of 1.0 ± 0.2 ppmv ($27 \pm 6\%$) in the LS during 1980–2010 with significant shorter-term variations along the way (Oltmans et al., 2000; Rosenlof et al., 2001; Hurst et al., 2011 and references herein) and its possible connection to the negative trend of temperature in the LS (WMO, 2007).

In 2009, Liu and Zipser (2009) investigated the implications of day (13:30 local time) vs. night (01:30 local time) differences of both H₂O and carbon monoxide (CO) in the TTL using 4 yr Microwave Limb Sounder (MLS) version 2.2 datasets. Their analysis showed H₂O and CO diurnal variations in the UT consistent with that of vertical transport by deep convection. Larger water vapour and CO concentrations were found at night than during the day, because of the convective uplift in the afternoon and the

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early evening. Both concentrations are observed to decrease with the weakening of convection and the horizontal mixing, resulting in a minimum around local noon. Diurnal variations were also observed at higher levels in the TTL but, while the CO concentration remained the largest at night, that of H₂O was found largest during the day. Since H₂O and CO are lofted simultaneously, Liu and Zipser (2009) hypothesised that H₂O was transformed into ice. Their diurnal variations in the TTL were then associated to the diurnal cycle of temperature, itself linked to the diurnal cycle of the cooling resulting from convective lofting of adiabatically cooled air.

Our analyses adopt the Liu and Zipser (2009) philosophy to discuss the difference between daytime and night-time datasets with the aim to better apprehend the role of continental convection on hydrating and dehydrating processes in the TTL. Our work is however based on twice-longer datasets, spanning over 8 yr, from 2005 to 2012, and from an improved version (v3.3, see Sect. 2.1) of MLS H₂O, ice water clouds (IWC) and temperature. Moreover, we separate the northern and southern tropics during their respective summer convective seasons: (i) June, July and August, hereafter JJA and (ii) December, January and February, hereafter DJF, respectively, rather than studying the full inter-tropical belt mixing all seasons. Thanks to this distinction, we were able to match separately H₂O and IWC variations in the Northern and Southern Hemispheres, both in DJF and JJA. 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. This regional scale approach offers the opportunity to confront the effects of convection over continental areas (South America and Africa), continental-oceanic regions (maritime continent) and oceans (Western Pacific) on H₂O, IWC and temperature, and analyse their differences on hydrating and dehydrating processes.

The paper is organised as follows. Section 2 investigates how convective systems impact H₂O and IWC diurnal variability in the UT, TTL and LS in different seasons, and the role of the temperature. Six regional scale areas (north tropical and south tropical South America, Africa and maritime continent) are compared in term of hydration or

dehydration and H₂O variability from the UT to the LS in Sect. 3. Relationships between H₂O, IWC and temperature are discussed in Sect. 4 followed by conclusions in Sect. 5. An Appendix presenting an analysis focusing on a pure oceanic case finalises the paper.

2 Water vapour, ice water clouds and temperature diurnal variability

The water vapour in the UT (146 hPa) and the TTL (100 hPa) in the inter-tropical belt (20° N–20° S) has been studied by Liu and Zipser (2009) for the 2005–2008 period. They found, on average in September–November and in March–May, strong evidence of H₂O diurnal variations over land attributed to the diurnal cycle of convection intensity displaying maximum in late afternoon followed by a morning decrease (Liu and Zipser, 2005). The H₂O lofted in the UT by convective systems was shown rising until late night and then dropping to a minimum around local noon when convection is the weakest. Figure 1 schematically summarises this interplay between diurnal variations of convective systems and H₂O in the UT. In the TTL, the largest H₂O amount was observed in the early afternoon, which was attributed to the change from gas phase to ice phase when H₂O enters the TTL followed by the sublimation of ice crystals in the morning. For explaining this feature, Liu and Zipser (2009) suggested two hypotheses: (1) in situ ice formation when deep convection generates gravity waves that lift and cool the tropopause (Potter and Holton, 1995; Sherwood and Dessler, 2001) leading to the dehydration of the TTL in late afternoon, a process known as “freeze and dry”, and (2) “ice geysers” that can directly inject ice crystals formed in the adiabatically cooled core of the overshoot turrets potentially hydrating the TTL after being sublimated (Corti et al., 2008; Khaykin et al., 2009). Both hypotheses result in a cooling of the TTL consistent with the results of Khaykin et al. (2013). Following Liu and Zipser (2009), the H₂O diurnal variability in the tropics has been investigated here using an extended and improved MLS dataset described in the following section. In our study, the UT is defined by pressure greater than or equal to 146 hPa, the TTL at pressure ranging from

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121 to 68 hPa and the LS at pressure less than or equal to 56 hPa, corresponding to the MLS pressure levels. A more qualitative definition of the TTL could be from few hPa below the level of zero radiative heating (LZRH) (Folkens et al., 1999) to few hPa above the cold point (CP) temperature.

2.1 Methodology

In this study, we used the Level 2 (L2) version 3.3 (v3.3) water vapour mixing ratio operational product of the Microwave Limb Sounder (MLS) aboard the NASA's Earth Observing System (EOS) AURA platform. AURA is a sun-synchronous near polar orbiter completing 233 revolution cycles every 16 days which results in a daily global coverage with about 14 orbits, allowing samplings at night-time at 01:30 local time (LT) and at daytime at 13:30 LT at the equator (Barnes et al., 2008). The MLS H₂O version 2.2 (v2.2) products have been validated (Read et al., 2007; Lambert et al., 2007), but the differences between v2.2 and v3.3 used here are minor in the tropics at the TTL pressure levels (< 10 %) (Livesey et al., 2011). From the UT (220 hPa) to the LS (31 hPa), the precision and accuracy range from 40 to 6 % and from 25 to 4 %, respectively, for a vertical resolution from 2.5 to 3.2 km, although the entire useful pressure range spans from 316 to 0.002 hPa (Livesey et al., 2011). Note that a data screening as suggested by Livesey et al. (2011) has been applied.

The v3.3 IWC product used here is derived from MLS cloud-induced radiances as detailed by Wu et al. (2006). It has a 3 km vertical resolution, a 1.2-to-0.07 mg m⁻³ precision and a 100–150 % accuracy in the pressure range 215–83 hPa where they are reliable (Livesey et al., 2011). The v3.3 IWC only differs from the v2.2 (Wu et al., 2008) by a 5–20 % negative bias in the 215–100 hPa layer and a larger random noise. The screenings suggested by Livesey et al. (2011) consisting in a temperature profile filter (Schwartz et al., 2008) and a “2 σ –3 σ ” screening method described by Wu et al. (2008) have been also applied.

The v3.3 temperature, very similar to the v2.2 described by Schwartz et al. (2008), has a useful domain ranging from 261 to 0.001 hPa. In the layer of interest for our

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and north tropical Africa (up to 10%), while the D-N drops to near 0% over oceans and in the Southern Hemisphere. Remarkably, the amplitude of the diurnal variability is 5–10% larger in south than in the north during their respective summer season.

At higher levels, at 100 hPa in the TTL and 56 hPa in the LS, the picture is out of phase with that of the UT, displaying H₂O daytime maxima over south tropical South America and south tropical Africa in DJF and small diurnal variation or night-time maxima elsewhere. Such H₂O continental daytime maxima are not seen at 100 hPa in JJA over north tropical Africa and northern South America (where the tropospheric H₂O peaks at 01:30 LT), but at 56 hPa in the south edge of the Tibetan anticyclone in the Asian monsoon region, however in the absence of daytime tropospheric moistening signal. A possible explanation for that could be the daytime sublimation of high thin cirrus clouds resulting from the hydration of the LS by wet parcels first lifted by convection over the Bay of Bengal and the Sea of China and then transported through the TTL via the monsoon anticyclonic circulation towards North-West India (Randel and Park, 2006; James et al., 2008; Wright et al., 2011).

In summary, with the exception of the Asian monsoon region, a marked night-time (daytime) water vapour increase is observed in the UT (TTL and LS) in summer over continental areas where convection is the most intense, remarkably of larger amplitude in the Southern than the Northern Hemisphere.

2.3 Tropical ice water cloud

Figure 3 is a plot similar to Fig. 2 but for IWC at 177 and 100 hPa. The black dashed and black solid lines are representing the contours of the IWC occurrences (15 and 50%, respectively). At both levels in DJF, the IWC occurrence frequency is the highest over South America, south tropical Africa and the maritime continent. IWC does show also a systematic diurnal cycle with daytime maxima above continental areas and night-time maxima over the maritime continent that is in phase with the known different diurnal cycle of convection over land and ocean. Remarkably, the amplitude of the IWC diurnal cycle is larger at 100 hPa than at 177 hPa. In JJA, the maximum occurrence frequen-

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cies are shifted to the northern tropics, over Central America, Central Africa and the South East Asian monsoon region. These observations are in agreement with previous studies characterising the distribution of cirrus clouds (Nazaryan et al., 2008; Sassen et al., 2008). The regions of early afternoon maxima are restricted to Amazonia, Central Africa and South Asia that is again over land convective areas, in contrast to the oceanic cycle.

In summary, the MLS IWC is showing a systematic diurnal cycle of maximum amplitude in the TTL at 100 hPa in phase with the diurnal cycle of convective development in the early afternoon over continents and early morning above oceans as shown in Fig. 1.

2.4 Role of the temperature

The MLS temperature at 100 hPa averaged in the same way as H₂O is shown in Fig. 2 (192 K solid lines and 195 K dashed lines). At this level, the temperature is lower in DJF over the equatorial South America and Africa, the maritime continent and the Western Pacific than in JJA where no significant cooling is observed above most intense continental convective areas. As shown by Khaykin et al. (2013) from the COSMIC satellites GPS Radio Occultation measurements, the temperature in the LS is displaying a systematic cooling (0.6 K) in the late afternoon above Southern Hemisphere convective continents, consistent with the positive continental signature of H₂O D-N (Fig. 2), in contrast to oceanic areas where the diurnal variation is insignificant. In JJA in the northern tropics, such event is limited to Central Africa and does not appear elsewhere. The afternoon LS cooling over land is consistent with the diurnal cycle of OPFs (Liu and Zipser, 2005) and with radiosonde observations near strong land convective systems reported in South East Brazil (Pommereau and Held, 2007; Pommereau, 2011), Central Africa (Khaykin et al., 2009; Cairo et al., 2010), Borneo Island (Johnson and Kriete, 1982) and Northern Australia (Danielsen, 1993). Such cooling was suggested by Danielsen (1982) to result from the overshooting of adiabatically cooled air across the tropopause. The larger amplitude of the cooling over Amazonia and Central

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Africa would imply a much more intense convection over clean rain forest areas compared to the aerosol-rich northern continental troposphere. As proposed by Khaykin et al. (2013), the possible explanation for that might be the larger optical thickness of the northern tropics attenuating the solar radiation at the surface, thus reducing the CAPE (Convective Available Potential Energy) as suggested by Rosenfeld et al. (2008).

3 Water vapour seasonal variations over land areas

If of convective origin, the H_2O , IWC and temperature diurnal cycles, of maximum amplitude over land, described in the previous section, should imply systematic seasonal cycles over land areas and moreover, differences between them. These seasonal cycles are investigated in the following sections.

3.1 Methodology

Six boxes of 10° latitude \times 20° longitude have been created, respectively over south tropical South America [$0\text{--}10^\circ$ S, $55\text{--}75^\circ$ W], south tropical Africa [$0\text{--}10^\circ$ S, $15\text{--}35^\circ$ E], and south tropical maritime continent [$0\text{--}10^\circ$ S, $110\text{--}130^\circ$ E], in the SH, and at the same longitudes, respectively over north tropical South America [$0\text{--}10^\circ$ N, $55\text{--}75^\circ$ W], north tropical Africa [$0\text{--}10^\circ$ N, $15\text{--}35^\circ$ E], and north tropical maritime continent [$0\text{--}10^\circ$ N, $110\text{--}130^\circ$ E] in the NH, as represented in the upper right panel of Fig. 2. The results from two boxes, representative of a pure oceanic area, located in the Western Pacific [$0\text{--}10^\circ$ S, $150\text{--}170^\circ$ E] and [$0\text{--}10^\circ$ N, $150\text{--}170^\circ$ E] are shown in the Appendix A. The MLS H_2O v3.3 dataset has been monthly averaged within each box from January 2005 to December 2012. For better focusing on seasonal cycles, the inter-annual variability such as that related to the quasi-biennial oscillation (QBO) or the El Niño-Southern Oscillation (ENSO) (Liang et al., 2011) and the semi-annual oscillation (SAO) (Delisi and Dunkerton, 1988), have been removed by filtering their contributions by applying a Fast Fourier Transform (FFT) of 12 ± 2 months band-pass. Moreover, from the filtered

contrast, the maritime continent TTL and LS are showing a different picture: a daytime drying (-4.6%) up to 90 hPa surmounted by a slight H_2O daytime increase (2.6%) around the Cold Point between 90–60 hPa and again a drying above.

Finally, the anomaly compared to the 2005–2012 mean H_2O mixing ratio (lower panels), does show a decrease with height from up to $\pm 28.7\%$ to 0% in the UT, and a local maximum in the TTL consistent with the seasonal cycle of the CP temperature ($\pm 33\%$ amplitude in all areas), surmounted in the LS by the tape recorder signature. Remarkably, the vertical propagation of the TTL summer maximum is very fast, almost simultaneous up to 68 hPa, and the time-lagged slow Brewer–Dobson ascent signature appears above that level only.

Another feature, which can be seen on the UT and TTL H_2O diurnal variation and on the UT anomaly, is the weakening (reinforcement) of the signal amplitude in 2008–2009 followed by its reinforcement (weakening) in 2009–2010 in the UT (TTL) above South America and Africa and the opposite above the maritime continent.

3.3 Water vapour in the Northern Hemisphere

As Fig. 4, Fig. 5 shows the cases of north tropical South America, Africa and maritime continent in the NH.

In the UT, the H_2O seasonal cycles (top panels) are similar to that of the SH displaying a summer maximum but of weaker amplitude (up to 29 ppmv in South America). Those of the TTL and the LS are also very similar with larger amplitude above South America and Africa compared to the maritime region. However, the diurnal variation features (middle panels) are significantly different: weaker night-time maximum humidity (up to 6% weaker than in the SH) in the UT and daytime maximum (up to 3% weaker than in the SH) in the TTL and LS above South America and almost absent in Africa. The only region where the northern and southern tropics are similar is the maritime continent. The monthly mean anomalies are similar to those of the SH, although of lesser amplitude in the UT than in the southern tropics (10 to 20% less than southern tropics). A remarkable feature seen in Figs. 4 and 5 is the height at which the tape

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recorder signal starts, that would imply a top TTL level, the stratosphere layer under influence of the troposphere, at about 68 hPa, at least above land areas.

Finally, as in the Southern Hemisphere, a weakening of amplitude followed by its reinforcement in the UT and conversely in the TTL, can be seen in both the diurnal variation and the anomaly in 2008–2009 and 2009–2010, respectively, above South America and Africa and maritime continent.

The El Niño and La Niña events do not appear in the Figs. 4 and 5 because of the filter applied to the data for removing inter-annual variations. However, by influencing the tropical circulation, these events indirectly perturb the D-N and anomaly amplitudes. Indeed, the weakening followed by the reinforcement of the diurnal cycle amplitude (middle panels Figs. 4 and 5) and the monthly mean anomaly (bottom panels) over land, and in turn, the opposite effect above the maritime continent, match with the ENSO events of 2006/07 and 2009/10 (Su and Jiang, 2013). 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 in the following 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 second (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 continental convective areas along with a 30 % drop above the maritime continent-Western Pacific in 2009/10. The changes in H₂O diurnal cycle and monthly mean anomalies amplitudes seen in Figs. 4 and 5 are thus consistent with the weakening of convection in the maritime continent and its strengthening in South America and Africa during the El Niño event, underlying further the convective origin of water vapour variations in the TTL and in the stratosphere.

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4 Discussion

In the previous sections, we presented the seasonal and diurnal variations of H₂O and IWC from the UT to the LS in the tropical band (20° N–20° S) first, and then focused on specific places of interest, namely, south tropical and north tropical South America, Africa and maritime continent. Below, we discuss the implications of these variations in the light of our observations and analyses to propose an interpretation in term of hydrating-dehydrating processes affecting the H₂O budget in the TTL and the LS.

Because the maritime continent and the Western Pacific are the areas of highest (~ 17 km, Khaykin et al., 2013), coolest (~ 190 K) and driest (2.5–3 ppmv) tropopause region with no sign of diurnal variation, its dehydration would be consistent with the condensation of the water vapour during the slow radiative ascent, the “Cold Trap” process proposed by Holton and Gettelman (2001). However, other processes are required for explaining the H₂O and IWC diurnal cycles in the TTL and the LS over land convective areas, whereas the late afternoon moistening and slight warming of the UT are known features resulting from the convective lofting of humid air leading to latent heat release when it condenses (Khaykin et al., 2013). As explained in Sect. 2.4, the late afternoon TTL and LS cooling by injection of adiabatic cooled air from overshooting convective systems suggested by Danielsen (1982) is also a well-understood feature which may have two implications: (1) the formation of cirrus clouds by condensation at temperature below saturation in the TTL at, or below, the cold point tropopause (Danielsen, 1982; Sherwood and Dessler, 2001), and/or (2) the generation of thin cirrus by injection of ice crystals further sublimating during the following day, moistening the TTL and LS. The daytime IWC maximum in the UT at 177 hPa and near the CP altitude at 100 hPa (Fig. 3) would be consistent with the first hypothesis while the daytime H₂O mixing ratio and temperature maxima in the TTL at 100 hPa and above in the LS, reported in Sects. 2 and 3, require the injection of water (ice crystals that later sublimate) across the tropopause, which the first scheme cannot provide.

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The H₂O mixing ratio, the amplitude of its diurnal cycle and of its monthly mean anomaly reported in Sects. 3.2 and 3.3, are all showing marked seasonal variations in the tropics out of phase in the UT on the one hand and in the TTL on the other. However in the UT, they are of systematic larger amplitude above land areas, particularly in South America and Africa in the SH and, although weaker, also in NH. A typical feature of these areas is the daytime maximum moistening in the TTL and LS. In contrast, both southern and northern maritime continents are displaying daytime drying of the TTL surmounted by moistening above. Like TTL and LS temperature diurnal cycles (Khaykin et al., 2013), the main differences between these areas are the convection characteristics: late afternoon maximum intensity over land and weak diurnal change over ocean (Fig. 1), implying a strong impact of land convection on humidity in the TTL and LS up to about 80 hPa. Moreover, the stronger signal in the SH summer particularly above South America would imply much more intense convection there than in the NH. The variability of the anomaly in the TTL and LS in all areas, which remains unchanged whatever the strength of the convection, is consistent with the variability of the CP temperature (Sects. 3.2 and 3.3). It implies that the continental convection does not affect the H₂O content on a seasonal timescale but deeply impacts its diurnal cycle in the TTL and LS.

In order to identify the hydration-dehydration processes responsible for the observed diurnal H₂O cycles, Fig. 6 shows on top the 2 month running averages from 2005 to 2012, of H₂O, IWC and temperature at 177 hPa in the UT, 100 hPa in the TTL and 56 hPa in the LS above the three south tropical areas where the convection is the most intense, and on bottom that of daytime and night-time H₂O anomalies compared to the monthly mean mixing ratio. At all longitudes at 177 hPa in the UT, the H₂O mixing ratio and IWC (top Fig. 6) are similar, displaying maxima in summer (October–March), whereas the temperature is slightly lower in winter (August–October) and in summer (January–March) than the other months. The picture is different at 100 hPa where H₂O and temperature variations are in phase (correlation > 0.9) displaying a maximum in winter/early spring (May–October), whereas IWC varies in phase with H₂O at 177 hPa

in the UT but out of phase at 100 hPa (correlation > 0.8 and < -0.6 , respectively). At 56 hPa, where there is no IWC information, H_2O is out of phase with the temperature (correlation < -0.8).

The bottom panels of Fig. 6 are showing the seasonal variations of the daytime and night-time H_2O mixing ratio over the same areas. In the UT at 177 hPa, its amplitude is maximum in the summer (October–March) over South America and Africa, in phase with the diurnal cycle of convection, of lesser amplitude above the maritime continent and absent in the West Pacific (see Appendix A). It is of opposite sign (daytime moistening) in the summer at 100 hPa in the TTL, above the two land convective regions, whereas it shows a daytime drying in winter, and of slight or insignificant daytime drying 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, absent everywhere else, showing night-time maximum. While the night-time moistening at these levels above oceanic areas during the whole year and continental regions in the winter are consistent with a condensation-sublimation diurnal cycle related to the radiative heating rate cycle of cirrus clouds (Hartmann et al., 2001; Corti et al., 2006), the daytime moistening at both 100 and 56 hPa above continents during the convective summer requires an hydration process. The only known mechanism compatible for hydrating these two layers is the convective overshooting of ice crystals at and above the tropopause, later sublimating the next day until the next cycle of convection.

5 Conclusions

Following the study of the water vapour diurnal cycle in the upper troposphere by Liu and Zipser (2009) from the MLS measurements, the same data, but on a twice longer period and a new version (8 yr instead of 4 and version 3 instead of 2), as well as temperature and IWC products, have been used for investigating the origin of the changes in H_2O concentration from the UT to the LS and specifically the possible contribution of

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tropical land convection on the tropical tropopause layer and lower stratosphere budget. In agreement with Liu and Zipser findings, MLS data are showing a night-time maximum moistening ($\sim 20\%$) of the UT above continental areas in the southern tropics during the austral summer in DJF and, although of a lesser extent ($\sim 10\%$), above the maritime continent. A similar signal is observed in the NH in JJA, but of lesser amplitude (5–10%). In the TTL and the LS, the humidity shows a daytime maximum moistening (up to 5–6%) over south tropical lands in the summer, out of phase with the UT signal, requiring a hydration process of those layers. The coincidence in location and timing of the maximum development of convection and the absence of other possible explanation, suggest that the daytime hydration above the tropopause is resulting from the late afternoon and early evening known convective overshooting ice crystals updrafts in the LS sublimating during the night and the following morning. Remarkably, such feature does not appear in the northern tropics during the convective season in JJA suggesting that convective overshoots are less frequent or less vigorous in the NH. An exception to this explanation is the observed daytime moistening over the Asian monsoon region at 56 hPa in the absence of similar signals at 100 hPa and 177 hPa requiring another hydration process there, which might result from the sublimation of cirrus clouds lofted and advected around the upper tropospheric anticyclone over the Tibetan Plateau.

The convective origin of the hydration of the TTL and LS over south tropical land is confirmed by the seasonal variations of daytime and night-time humidity at these levels over the various south tropical regions showing that the daytime hydration is restricted to summer south tropical America and Africa, and although of less intensity over the maritime continent, compared to all other locations and seasons in both hemispheres where the maximum water vapour is mostly observed during daytime, consistent with the condensation/evaporation daily cycle of radiative heating origin.

In summary, the MLS water vapour, ice water cloud and temperature observations are demonstrating a clear contribution of TTL and lower stratosphere moistening by

ice crystals overshooting updrafts over land tropical regions and the much greater efficiency of the process in the Southern Hemisphere.

Appendix A

Western Pacific

5 The study of the south tropical Western Pacific helped us to identify the characteristics of pure oceanic areas with respect to the continental areas regarding the impact of the convection. In the UT, all parameters present maxima in summer in phase with the convection. In the TTL and the LS, the picture is similar to that of the maritime continent. The most interesting feature is the year-long positive value of the night-
10 time H₂O whatever the height, consistent with the oceanic diurnal cycle of convection maximum early morning (Fig. A1).

Acknowledgements. The work was supported by the French Agence Nationale de la Recherche (ANR) TROPICO project (<http://www.univ-reims.fr/TRO-pico/>). The data used in this effort were acquired as part of the activities of NASA's Science Mission Directorate, and are archived and distributed by the Goddard Earth Sciences (GES) Data and Information Services Center (DISC).
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References

- Alcala, C. M. and Dessler, A. E.: Observations of deep convection in the tropics using the Tropical Rainfall Measuring Mission (TRMM) precipitation radar, *J. Geophys. Res.*, 107, 4792, doi:10.1029/2002JD002457, 2002.
20 Barnes, J. E., Kaplan, T., Vömel, H., and Read, W. G.: NASA/Aura/Microwave Limb Sounder water vapor validation at Mauna Loa Observatory by Raman lidar, *J. Geophys. Res.*, 113, D15S03, doi:10.1029/2007JD008842, 2008.
- Brewer, A. W.: Evidence for a world circulation provided by the measurements of helium and water vapor distribution in the stratosphere, *Q. J. Roy. Meteor. Soc.*, 75, 351–363, 1949.
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- Cairo, F., Pommereau, J. P., Law, K. S., Schlager, H., Garnier, A., Fierli, F., Ern, M., Streibel, M., Arabas, S., Borrmann, S., Berthelot, J. J., Blom, C., Christensen, T., D'Amato, F., Di Donfrancesco, G., Deshler, T., Diedhiou, A., Durry, G., Engelsen, O., Goutail, F., Harris, N. R. P., Kerstel, E. R. T., Khaykin, S., Konopka, P., Kylling, A., Larsen, N., Lebel, T., Liu, X., MacKenzie, A. R., Nielsen, J., Oulanowski, A., Parker, D. J., Pelon, J., Polcher, J., Pyle, J. A., Ravegnani, F., Rivi re, E. D., Robinson, A. D., R ckmann, T., Schiller, C., Sim es, F., Stefanutti, L., Stroh, F., Some, L., Siegmund, P., Sitnikov, N., Vernier, J. P., Volk, C. M., Voigt, C., von Hobe, M., Viciani, S., and Yushkov, V.: An introduction to the SCOUT-AMMA stratospheric aircraft, balloons and sondes campaign in West Africa, August 2006: rationale and roadmap, *Atmos. Chem. Phys.*, 10, 2237–2256, doi:10.5194/acp-10-2237-2010, 2010.
- Chaboureau, J.-P., Cammas, J.-P., Duron, J., Mascart, P. J., Sitnikov, N. M., and Voessing, H.-J.: A numerical study of tropical cross-tropopause transport by convective overshoots, *Atmos. Chem. Phys.*, 7, 1731–1740, doi:10.5194/acp-7-1731-2007, 2007.
- Chemel, C., Russo, M. R., Pyle, J. A., Sokhi, R. S., and Schiller, C.: Quantifying the imprint of a severe hector thunderstorm during ACTIVE/SCOUT-O3 onto the water content in the upper troposphere/lower stratosphere, *Mon. Weather Rev.*, 137, 2493–2514, doi:10.1175/2008MWR2666.1, 2009.
- Corti, T., Luo, B. P., Fu, Q., V mel, H., and Peter, T.: The impact of cirrus clouds on tropical troposphere-to-stratosphere transport, *Atmos. Chem. Phys.*, 6, 2539–2547, doi:10.5194/acp-6-2539-2006, 2006.
- Corti, T., Luo, B. P., de Reus, M., Brunner, D., Cairo, F., Mahoney, M. J., Martucci, G., Matthey, R., Mitev, V., dos Santos, F. H., Schiller, C., Shur, G., Sitnikov, N. M., Spelten, N., Vossing, H. J., Borrmann, S., and Peter, T.: Unprecedented evidence for deep convection hydrating the tropical stratosphere, *Geophys. Res. Lett.*, 35, L10810, doi:10.1029/2008GL033641, 2008.
- Danielsen, E. F.: A dehydration mechanism for the stratosphere, *Geophys. Res. Lett.*, 9, 605–608, doi:10.1029/GL009i006p00605, 1982.
- Danielsen, E. F.: In situ evidence of rapid, vertical, irreversible transport of lower tropospheric air into the lower stratosphere by convective cloud turrets and by large scale up welling in tropical cyclones, *J. Geophys. Res.*, 98, 8665–8681, 1993.
- Delisi, D. P. and Dunkerton, T. J.: Seasonal variation of the semiannual oscillation, *J. Atmos. Sci.*, 45, 2772–2787, doi:10.1175/1520-0469(1988)045<2772:SVOTSO>2.0.CO;2, 1988.

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- Dessler, A. E.: The effect of deep, tropical convection on the tropical tropopause layer, *J. Geophys. Res.*, 107, D34033, doi:10.1029/2001JD000511, 2002.
- Folkins, I., Loewenstein, M., Podolske, J., Oltmans, S. J., and Proffitt, M.: A barrier to vertical mixing at 14 km in the tropics: evidence from ozoneondes and aircraft measurements, *J. Geophys. Res.*, 104, 22095–22102, 1999.
- 5 Fueglistaler, S., Wernli, H., and Peter, T.: Tropical troposphere-to-stratosphere transport inferred from trajectory calculations, *J. Geophys. Res.*, 109, D03108, doi:10.1029/2003JD004069, 2004.
- Fueglistaler, S., Dessler, A. E., Dunkerton, T. J., Folkins, I., Fu, Q., and Mote, P. W.: Tropical tropopause layer, *Rev. Geophys.*, 47, RG1004, doi:10.1029/2008RG000267, 2009.
- 10 Gettelman, A., Salby, M. L., and Sassi, F.: The distribution and influence of convection in the tropical tropopause region, *J. Geophys. Res.*, 107, 4080, doi:10.1029/2001JD001048, 2002.
- Grosvenor, D. P., Choularton, T. W., Coe, H., and Held, G.: A study of the effect of overshooting deep convection on the water content of the TTL and lower stratosphere from Cloud Resolving Model simulations, *Atmos. Chem. Phys.*, 7, 4977–5002, doi:10.5194/acp-7-4977-2007, 15 2007.
- Hartmann, D. L., Holton, J. R., and Fu, Q.: The heat balance of the tropical tropopause, cirrus, and stratospheric dehydration, *Geophys. Res. Lett.*, 28, 1969–1972, 2001.
- Hassim, M. E. E. and Lane, T. P.: A model study on the influence of overshooting convection on TTL water vapour, *Atmos. Chem. Phys.*, 10, 9833–9849, doi:10.5194/acp-10-9833-2010, 20 2010.
- Holton, J. R. and Gettelman, A.: Horizontal transport and the dehydration of the stratosphere, *Geophys. Res. Lett.*, 28, 2799–2802, 2001.
- Holton, J. R., Haynes, P. H., McIntyre, M. E., Douglass, A. R., Rood, R. B., and Pfister, L.: Stratosphere–troposphere exchange, *Rev. Geophys.*, 33, 403–439, 1995.
- 25 Hurst, D. F., Oltmans, S. J., Vömel, H., Rosenlof, K. H., Davis, S. M., Ray, E. A., Hall, E. G., and Jordan, A. F.: Stratospheric water vapor trends over Boulder, Colorado: analysis of the 30 year Boulder record, *J. Geophys. Res.*, 116, D02306, doi:10.1029/2010JD015065, 2011.
- James, R., Bonazzola, M., Legras, B., Surbled, K., and Fueglistaler, S.: Water vapor transport and dehydration above convective outflow during Asian monsoon, *Geophys. Res. Lett.*, 35, L20810, doi:10.1029/2008GL035441, 2008.
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Jensen, E. J., Ackerman, A. S., and Smith, J. A.: Can overshooting convection dehydrate the tropical tropopause layer?, *J. Geophys. Res.*, 112, D11209, doi:10.1029/2006JD007943, 2007.

Johnson, R. H. and Kriete, D. C.: Thermodynamic and circulation characteristics of winter monsoon tropical mesoscale convection, *Mon. Weather Rev.*, 10, 1898–1911, 1982.

Khaykin, S., Pommereau, J.-P., Korshunov, L., Yushkov, V., Nielsen, J., Larsen, N., Christensen, T., Garnier, A., Lukyanov, A., and Williams, E.: Hydration of the lower stratosphere by ice crystal geysers over land convective systems, *Atmos. Chem. Phys.*, 9, 2275–2287, doi:10.5194/acp-9-2275-2009, 2009.

Khaykin, S. M., Pommereau, J.-P., and Hauchecorne, A.: Impact of land convection on temperature diurnal variation in the tropical lower stratosphere inferred from COSMIC GPS radio occultations, *Atmos. Chem. Phys.*, 13, 6391–6402, doi:10.5194/acp-13-6391-2013, 2013.

Kim, W. M., Yeh, S. W., Kim, J. H., Kug, J. S., and Kwon, M. H.: The unique 2009–2010 El Niño event: a fast phase transition of warm pool El Niño to La Niña, *Geophys. Res. Lett.*, 38, L15809, doi:10.1029/2011GL048521, 2011.

Knollenberg, R. G., Kelly, K., and Wilson, J. C.: Measurements of high number of ice crystals in the tops of tropical cumulonimbus, *J. Geophys. Res.*, 98, 8639–8664, 1993.

Lambert, A., Read, W. G., Livesey, N. J., Santee, M. L., Manney, G. L., Froidevaux, L., Wu, D. L., Schwartz, M. J., Pumphrey, H. C., Jimenez, C., Nedoluha, G. E., Cofield, R. E., Cuddy, D. T., Daffer, W. H., Drouin, B. J., Fuller, R. A., Jarnot, R. F., Knosp, B. W., Pickett, H. M., Perrun, V. S., Snyder, W. V., Stek, P. C., Thurstans, R. P., Wagner, P. A., Waters, J. W., Jucks, K. W., Toon, G. C., Stachnik, R. A., Bernath, P. F., Boone, C. D., Walker, K. A., Urban, J., Murtagh, D., Elkins, J. W., and Atlas, E.: Validation of the Aura Microwave Limb Sounder middle atmosphere water vapor and nitrous oxide measurements, *J. Geophys. Res.*, 112, D24S36, doi:10.1029/2007JD008724, 2007.

Lee, T. and McPhaden, M. J.: Increasing intensity of El Niño in the central-equatorial Pacific, *Geophys. Res. Lett.*, 37, L14603, doi:10.1029/2010GL044007, 2010.

Liang, C., Eldering, A., Gettelman, A., Tian, B., Wong, S., Fetzer, E., and Liou, K.: Record of tropical interannual variability of temperature and water vapor from a combined AIRS-MLS data set, *J. Geophys. Res.*, 116, D06103, doi:10.1029/2010JD014841, 2011.

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

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Liu, C. and Zipser, E. J.: 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, 2009.

Liu, X. M., Rivière, E. D., Marécal, V., Durry, G., Hamdouni, A., Arteta, J., and Khaykin, S.: Stratospheric water vapour budget and convection overshooting the tropopause: modelling study from SCOUT-AMMA, *Atmos. Chem. Phys.*, 10, 8267–8286, doi:10.5194/acp-10-8267-2010, 2010.

Livesey, N. J.: EOS MLS Version 3.3 Level 2 data quality and description document, version 3.3 x-1.0, JPL D-33509, Jet Propul. Lab., Pasadena, Calif., 2011.

Mote, P. W., Rosenlof, K. H., Holton, J. R., Harwood, R. S., and Waters, J. W.: An atmospheric tape recorder: the imprint of tropical tropopause temperatures on stratospheric water vapor, *J. Geophys. Res.*, 101, 8651–8666, 1996.

Nazaryan, H., McCormick, M. P., and Menzel, W. P.: Global characterization of cirrus clouds using CALIPSO data, *J. Geophys. Res.*, 113, D16211, doi:10.1029/2007JD009481, 2008.

Newell, R. E. and Gould-Stewart, S.: A stratospheric fountain, *J. Atmos. Sci.*, 38, 2789–2795, 1981.

Oltmans, S. J., Vömel, H., Hofmann, D. J., Rosenlof, K. H., and Kley, D.: The increase in stratospheric water vapor from balloonborne, frostpoint hygrometer measurements at Washington, DC, and Boulder, Colorado, *Geophys. Res. Lett.*, 27, 3453–3456, 2000.

Pommereau, J.-P. and Held, G.: Is there a stratospheric fountain?, *Atmos. Chem. Phys. Discuss.*, 7, 8933–8950, doi:10.5194/acpd-7-8933-2007, 2007.

Pommereau, J.-P., Garnier, A., Held, G., Gomes, A. M., Goutail, F., Durry, G., Borch, F., Hauchecorne, A., Montoux, N., Cocquerez, P., Letrenne, G., Vial, F., Hertzog, A., Legras, B., Pissot, I., Pyle, J. A., Harris, N. R. P., Jones, R. L., Robinson, A. D., Hansford, G., Eden, L., Gardiner, T., Swann, N., Knudsen, B., Larsen, N., Nielsen, J. K., Christensen, T., Cairo, F., Fierli, F., Pirre, M., Marécal, V., Huret, N., Rivière, E. D., Coe, H., Grosvenor, D., Edvarsen, K., Di Donfrancesco, G., Ricaud, P., Berthelot, J.-J., Godefroy, M., Seran, E., Longo, K., and Freitas, S.: An overview of the HIBISCUS campaign, *Atmos. Chem. Phys.*, 11, 2309–2339, doi:10.5194/acp-11-2309-2011, 2011.

Potter, B. E. and Holton, J. R.: The role of monsoon convection in the dehydration of the lower tropical stratosphere, *J. Atmos. Sci.*, 52, 1034–1050, 1995.

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Randel, W. J. and Park, M.: Deep convective influence on the Asian summer monsoon anticyclone and associated tracer variability observed with Atmospheric Infrared Sounder (AIRS), *J. Geophys. Res.*, 111, D12314, doi:10.1029/2005JD006490, 2006.

Read, W. G., Wu, D. L., Waters, J. W., and Pumphrey, H. C.: Dehydration in the tropical tropopause layer: implications from the UARS Microwave Limb Sounder, *J. Geophys. Res.*, 109, D06110, doi:10.1029/2003JD004056, 2004.

Read, W. G., Lambert, A., Bacmeister, J., Cofield, R. E., Christensen, L. E., Cuddy, D. T., Daffer, W. H., Drouin, B. J., Fetzer, E., Froidevaux, L., Fuller, R., Herman, R., Jarnot, R. F., Jiang, J. H., Jiang, Y. B., Kelly, K., Knosp, B. W., Kovalenko, L. J., Livesey, N. J., Liu, H. C., Manney, G. L., Pickett, H. M., Pumphrey, H. C., Rosenlof, K. H., Sabounchi, X., L. Santee, M., Schwartz, M. J., Snyder, W. V., Stek, P. C., Su, H., Takacs, L. L., Thurstans, R. P., Vomel, H., Wagner, P. A., Waters, J. W., Webster, C. R., Weinstock, E. M., and Wu, D. L.: Aura Microwave Limb Sounder upper tropospheric and lower stratospheric H₂O and relative humidity with respect to ice validation, *J. Geophys. Res.*, 112, D24S35, doi:10.1029/2007JD008752, 2007.

Ricaud, P., Barret, B., Attié, J.-L., Motte, E., Le Flochmoën, E., Teysse, H., Peuch, V.-H., Livesey, N., Lambert, A., and Pommereau, J.-P.: Impact of land convection on troposphere-stratosphere exchange in the tropics, *Atmos. Chem. Phys.*, 7, 5639–5657, doi:10.5194/acp-7-5639-2007, 2007.

Ricaud, P., Pommereau, J.-P., Attié, J.-L., Le Flochmoën, E., El Amraoui, L., Teysse, H., Peuch, V.-H., Feng, W., and Chipperfield, M. P.: Equatorial transport as diagnosed from nitrous oxide variability, *Atmos. Chem. Phys.*, 9, 8173–8188, doi:10.5194/acp-9-8173-2009, 2009.

Rosenfeld, D., Lohmann, U., Raga, G. B., O'Dowd, C. D., Kulmala, M., Fuzzi, S., Reissell, A., and Andreae, M.: Flood or drought: how do aerosols affect precipitation?, *Science*, 321, 1309–1313, 2008.

Rosenlof, K., Oltmans, S., Kley, D., Russell, J., Chiou, E.-W., Chu, W., Johnson, D., Kelly, K., Michelsen, H., Nedoluha, G. E., Remsberg, E. E., Toon, G. C., and McCormick, M. P.: Stratospheric water vapor increases over the past half-century, *Geophys. Res. Lett.*, 28, 1195–1198, 2001.

Russell, J. M., Gordley, L. L., Park, J. H., Drayson, S. R., Hesketh, W. D., Cicerone, R. J., Tuck, A. F., Frederick, J. E., Harries, J. E., and Crutzen, P. J.: The Halogen Occultation Experiment, *J. Geophys. Res.*, 98, 10777–10797, 1993.

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Schiller, C., Grooß, J.-U., Konopka, P., Plöger, F., Silva dos Santos, F. H., and Spelten, N.: Hydration and dehydration at the tropical tropopause, *Atmos. Chem. Phys.*, 9, 9647–9660, doi:10.5194/acp-9-9647-2009, 2009.

Schwartz, M., Lambert, A., Manney, G., Read, W., Livesey, N., Froidevaux, L., Ao, C., Bernath, P., Boone, C., Cofield, R., Daffer, W. H., Drouin, B. J., Fetzer, E. J., Fuller, R. A., Jarnot, R. F., Jiang, J. H., Jiang, Y. B., Knosp, B. W., Kruger, K., Li, J.-L. F., Mlynchzak, M. G., Pawson, S., Russell III, J. M., Santee, M. L., Snyder, W. V., Stek, P. C., Thurstans, R. P., Tompkins, A. M.P., Wagner, A., Walker, K. A., Waters, J. W., and Wu, D. L.: Validation of the Aura Microwave Limb Sounder temperature and geopotential height measurements, *J. Geophys. Res.-Atmos.*, 113, D15S11, 1984–2012, doi:10.1029/2007JD008783, 2008.

Sherwood, S. C. and Dessler, A. E.: On the control of stratospheric humidity, *Geophys. Res. Lett.*, 27, 2513–2516, 2000.

Sherwood, S. C. and Dessler, A. E.: A model for transport across the tropical tropopause, *J. Atmos. Sci.*, 58, 765–779, 2001.

Sherwood, S. C. and Dessler, A. E.: Convective mixing near the tropical tropopause: insights from seasonal variations, *J. Atmos. Sci.*, 60, 2674–2685, 2003.

Solomon, S., Rosenlof, K. H., Portmann, R. W., Daniel, J. S., Davis, S. M., Sanford, T. J., and Plattner, G. K.: Contributions of stratospheric water vapor to decadal changes in the rate of global warming, *Science*, 327, 1219–1223, 2010.

Su, H. and Jiang, J. H.: Tropical clouds and circulation changes during the 2006/07 and 2009/10 El Niños, *J. Climate*, 26, 399–413, 2013.

Vernier, J.-P., Pommereau, J.-P., Thomason, L. W., Pelon, J., Garnier, A., Deshler, T., Jumelet, J., and Nielsen, J. K.: Overshooting of clean tropospheric air in the tropical lower stratosphere as seen by the CALIPSO lidar, *Atmos. Chem. Phys.*, 11, 9683–9696, doi:10.5194/acp-11-9683-2011, 2011.

Weinstock, E. M., Hints, E. J., Dessler, A. E., and Anderson, J. G.: Measurements of water vapor in the tropical lower stratosphere during the CEPEX campaign: results and interpretation, *Geophys. Res. Lett.*, 22, 3231–3234, 1995.

WMO: Scientific assessment of Ozone Depletion: 2006, Global Ozone Research and Monitoring Project, Report No. 50, 572 pp., Geneva, 2007.

Wright, J. S., Fu, R., Fueglistaler, S., Liu, Y. S., and Zhang, Y.: The influence of summertime convection over Southeast Asia on water vapor in the tropical stratosphere, *J. Geophys. Res.*, 116, D12302, doi:10.1029/2010JD015416, 2011.

Wu, D. L., Jiang, J. H., and Davis, C. P.: EOS MLS cloud ice measurements and cloudy-sky radiative transfer model, *IEEE T. Geosci. Remote*, 44, 1156–1165, 2006.

Wu, D. L., Jiang, J. H., Read, W. G., Austin, R. T., Davis, C. P., Lambert, A., Stephens, G. L., Vane, D. G., and Waters, J. W.: Validation of the Aura MLS cloud ice water content measurements, *J. Geophys. Res.*, 113, D15S10, doi:10.1029/2007JD008931, 2008.

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13, 33055–33087, 2013

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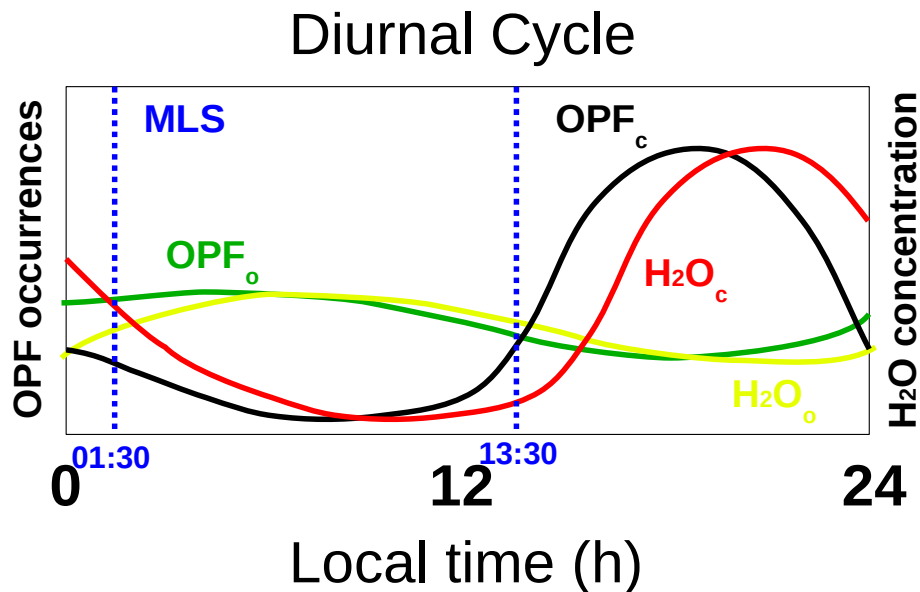


Fig. 1. Schematic representation adapted from Liu and Zipser (2005) of the Overshooting Precipitation Features (OPF) diurnal cycle in the UT above continental areas (OPF_c, black solid line) and above oceanic areas (OPF_o, green solid line) with the expected H₂O diurnal cycle above continental areas (H₂O_c, red solid line) and above oceanic areas (H₂O_o, yellow solid line). Blue dotted lines show the MLS sampling local time.

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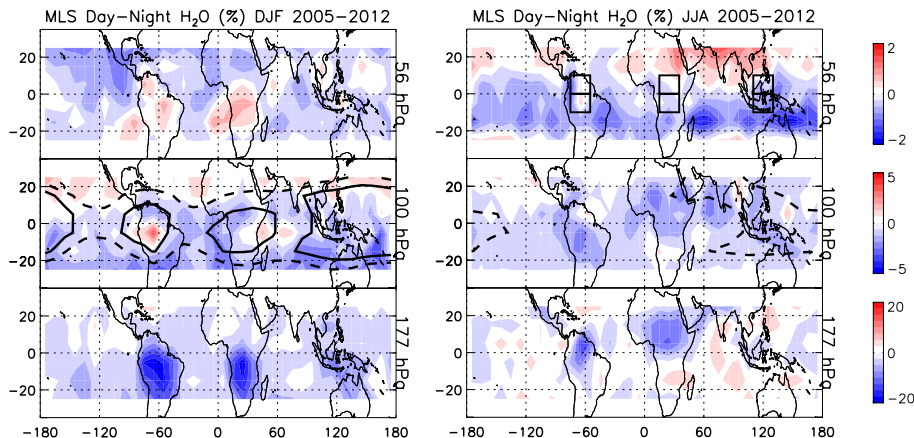


Fig. 2. (Left, from top to bottom) Mean relative difference between the daytime (13:30 LT) and night-time (01:30 LT) MLS H_2O measurements for December, January and February for 8 yr (2005–2012) in the 25°N – 25°S latitude band at 56, 100 and 177 hPa. The 192 K (black solid line) and 195 K (black dashed line) temperature contours are represented at 100 hPa. (Right) Same as left but for June, July and August. The six black boxes at 56 hPa represent the six areas of study, namely northern and southern South America, northern and southern Africa, northern and southern maritime continent.

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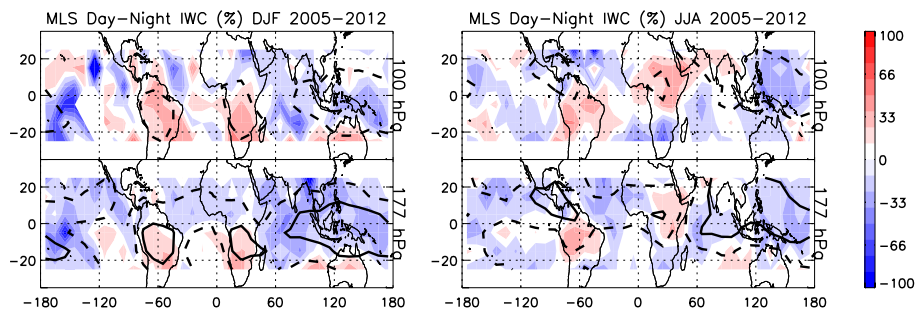


Fig. 3. Same as Fig. 2 but for IWC at 177 hPa and 100 hPa. The solid black and dashed black lines represent the IWC occurrences (50 % and 15 %, respectively).

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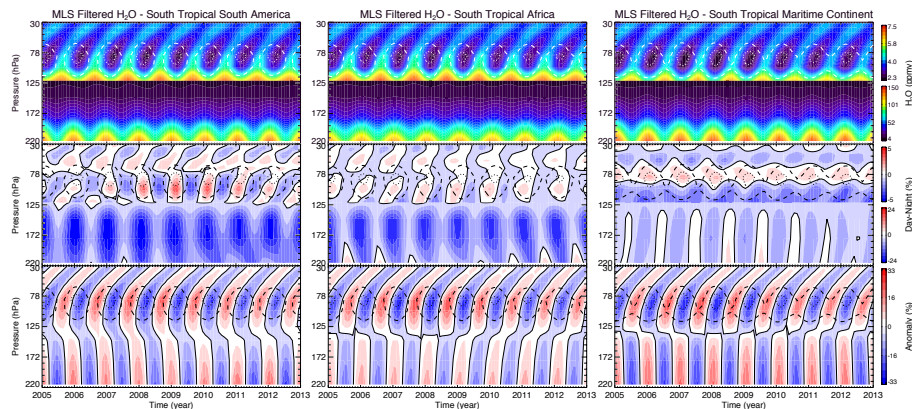


Fig. 4. (Left, from top to bottom) MLS 2005 to 2012 monthly-averaged filtered H_2O , relative filtered D-N and relative filtered anomaly time series from 220 to 30 hPa in south tropical South America. The white (top) and black (middle and bottom) dashed lines show the filtered temperature 195 K contour. The white (top) and black (middle and bottom) dotted lines show the filtered temperature 190 K contour. Note the use of a reduced colour scale from 121 to 30 hPa for the top and middle figures. (Middle) Same as left but for south tropical Africa. (Right) Same as left but for south tropical maritime continent.

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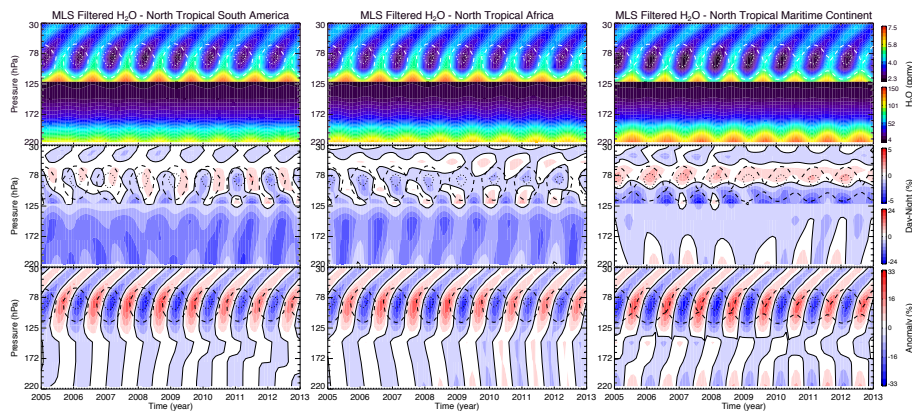


Fig. 5. Same as Fig. 4 but for north tropical South America (left), north tropical Africa (middle) and north tropical maritime continent (right).

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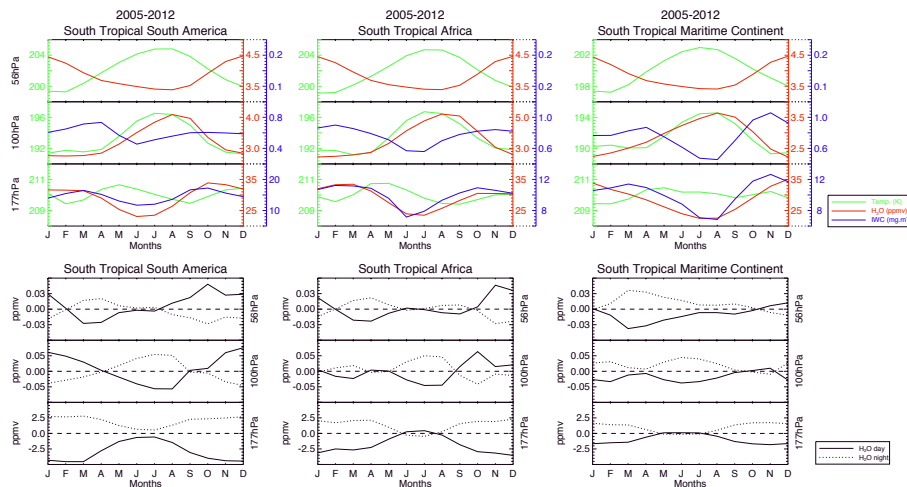


Fig. 6. (Top, from left to right) MLS 2 month running average, from 2005 to 2012, H₂O (red line), temperature (green line) and IWC (blue line) from January to December at 56 hPa (top), 100 hPa (middle) and 177 hPa (bottom) in south tropical South America, Africa and maritime continent. (Bottom, from left to right) monthly H₂O daytime (solid line) and H₂O night-time (dotted line) anomalies, calculated for each month as the difference between the monthly average daytime (night-time) H₂O and the monthly average H₂O, for the 2005–2012 period, at 177, 100 and 56 hPa in south tropical South America, Africa and maritime continent.

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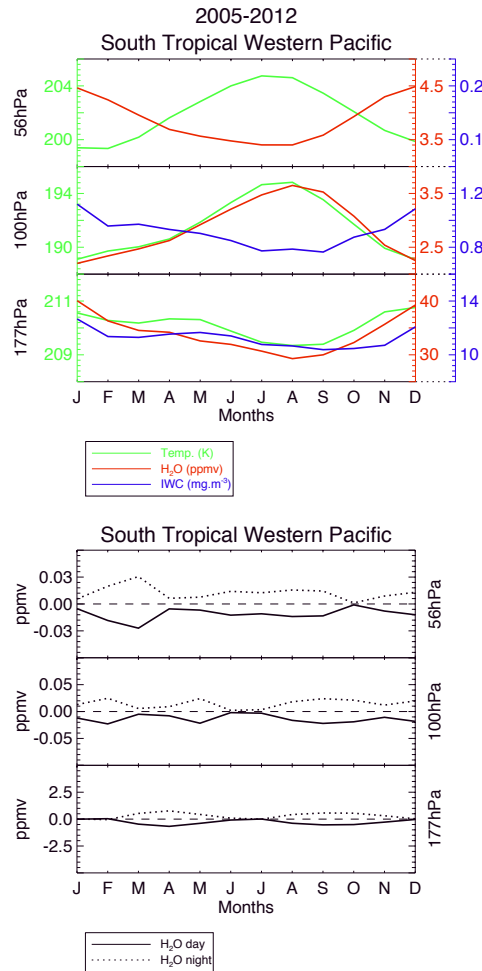


Fig. A1. Same as Fig. 6 but for the Western Pacific.



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