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Correlation among cirrus ice content, water vapor and temperature in the TTL as observed by CALIPSO and Aura/MLS

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Abstract

Water vapor in the tropical tropopause layer (TTL) has a significant radiative cooling effect on the Earth's climate system. As a source for cirrus clouds, however, it can also indirectly produce infrared heating. The amount of water vapor in the TTL is strongly controlled by temperature (correlation $r = 0.94$) with a seasonal cycle of $\sim$ 1–2 ppm vmr in amplitude at 100 hPa and minimum values in Northern Hemisphere winter (December-January-February, DJF). Studying the A-Train CALIPSO cirrus and MLS water vapor measurements, we find that the cirrus seasonal cycle is highly ($r = -0.9$) anticorrelated with the water vapor variation in the TTL, showing higher cloud occurrence during DJF. We further investigate the anticorrelation on a regional scale and find that the high anticorrelation occurs generally in the ITCZ (Intertropical Convergence Zone). The seasonal cycle of the cirrus ice water content is also highly anticorrelated to water vapor ($r = -0.91$) and our results support the hypothesis that the total water is roughly constant in the TTL at 100 hPa. Temperature acts as a main regulator for balancing the partition between water vapor and cirrus clouds. Thus, to a large extent, the depleting water vapor in the TTL during DJF is a manifestation of cirrus formation.

1 Introduction

Water vapor (H_2O) is a key constituent of the Earth atmosphere and climate system. It is the dominant greenhouse gas and has important impacts on atmospheric circulations through latent heat exchanges and redistribution of energy (Schneider et al., 2010). As a source of clouds, water vapor has an indirect effect on the surface longwave and shortwave radiation budget.

Water vapor is also important for the radiative balance and chemistry in the stratosphere (de F. Forster and Shine, 1999). An increase in stratospheric water vapor tends to cool the stratosphere due to more longwave emission to space. Recent decadal records show that stratospheric water vapor has been increasing (Solomon et al., 2010;

ACPD
11, 25037–25061, 2011

Rosenlof et al., 2001) and it is still under debate how water vapor reaches the stratosphere (Chae et al., 2011). It is widely accepted that water vapor enters the stratosphere through the tropical tropopause layer (TTL), which is the layer on top of the main cumulus outflow extending to ~ 1 km above the thermal tropopause. The TTL extends approximately from 14 km ($p = 150$ hPa, $\Theta = 355$ K) to 18.5 km altitude (70 hPa, 425 K) (Fueglistaler et al., 2009) representing a mixed layer having both tropospheric and stratospheric characteristics. The bottom of the TTL is usually defined by the level of zero net radiative heating. Above this level air tends to rise by radiative heating whereas below, it tends to sink. The top of the TTL is the maximum height of overshooting convection.

Convection brings water vapor into the TTL and the interplay between transport and freeze-drying controls the amount of water vapor lifted into the stratosphere (Read et al., 2008). Yang et al. (2010) suggest that water vapor from overshooting convection can be radiatively lifted up to the stratosphere which is supported by measurements of Grosvenor et al. (2007) and Corti et al. (2008). Thus stratospheric water vapor is closely linked to convection and vertical ascent in the TTL.

The ascent of TTL air is predominantly regulated by cirrus clouds that provide the necessary radiative heating to balance the adiabatic cooling produced by the slow ascent of air that enters the stratosphere (Jensen et al., 2010). Cirrus above convective cumulus clouds prevail much longer in the atmosphere than the anvils below (Garrett et al., 2004) and have a warming effect on the surface (Jensen et al., 2010). It is thus crucial to know the water budget as well as the form of water in the TTL when it comes to determine its effect on surface warming since water vapor and cirrus have opposite effects (Solomon et al., 2010). Wang et al. (1996) already stated that cirrus clouds are more frequent during Northern Hemisphere (NH) winter which is also the season for lowest TTL water vapor volume mixing ratios and lowest temperatures. Dessler et al. (2006) showed by using ICESat measurements that thin TTL thin cirrus occur frequently between 20° S and 30° N with distinct maxima over regions of intense convection.

ACPD
11, 25037–25061, 2011

Randel et al. (2004) showed that temperature and water vapor are correlated (r = 0.73) in the TTL using NCEP temperatures and UARS/HALOE satellite water vapor data. In this study we further investigate the roles of temperature in regulating the water partition between vapor and ice, not only for the TTL but also on a regional basis. We seek to better quantify the amount of cirrus clouds that can serve as a reservoir for TTL water vapor. For this puropse we use data from the NASA A-Train satellite instruments MLS and CALIOP and determine the correlation of water vapor, cirrus cloud fraction and ice water content in the TTL in the years 2006–2011. Section 2 presents the data and method whereas Sect. 3 presents the results from the correlation studies. In Sect. 4 we discuss our findings and conclude in Sect. 5.

2 Data and method

In this study we use water vapor and cloud data from the NASA A-Train satellite instruments MLS (Microwave Limb Sounder) on Aura and CALIOP (Cloud-Aerosol Lidar with Orthogonal Polarization) on CALIPSO (Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation), respectively. The data cover the time period from June 2006 (start of CALIPSO) to February 2011. MLS water vapor is retrieved from 316 hPa to 0.002 hPa from 82° S to 82° N. The data have been validated by Read et al. (2007). We use daily version 2.2 (v.2.2) data. MLS has a horizontal resolution of 200–300 km along track, 7 km across track and 3–4 km in the vertical. The fields are averaged and mapped onto a 4° latitude and 8° longitude grid. For this study we use the vertical levels of 147 hPa, 121 hPa, 100 hPa, 83 hPa, 68 hPa, 56 hPa, 46 hPa, 38 hPa, 32 hPa, 26 hPa and 22 hPa but the study focuses on 100 hPa in the tropics.

CALIPSO cloud occurrence frequency and Ice Water Content (IWC) level 2 data are of version 3. This data has a horizontal resolution of 5 km and 60 m in the vertical (Winker et al., 2007). We binned the data to the coarser MLS grid described above. Only nighttime cloud data is used for the TTL cloud analysis because of excessive noise during daytime (Wu et al., 2011). NCEP reanalysis temperature is used for the correlation study with water vapor presented in section 3.1. The NCEP data is provided on a 2.5° by 2.5° horizontal grid and on pressure levels from 1000 hPa to 10 hPa, but is also interpolated to the MLS horizontal and vertical grid.

In the following analysis we use daily Aura/MLS H_2O and NCEP temperature data. Monthly and seasonal averages are determined out of the daily satellite and reanalysis data and used for the correlation studies. The covered time period consists of 57 months which makes a total of 19 seasons. Hence the main results of our study rely on the 19 season time series whilst only one result is based on the daily data, namely the correlation of temperature and water vapor in Sect. 3.1.

3 Results

3.1 Water vapor dependence on temperature

Air masses entering the stratosphere in the tropics must pass through the low temperature at the tropopause with substantial dehydration. This was first recognized by Brewer (1949) after he had observed surprisingly low water vapor concentrations in the lower stratosphere. The process of temperature dependent dehydration can be observed in the so called atmospheric tape recorder (Mote et al., 1996). The variations in TTL water vapor are slowly carried upward into the stratosphere and the signal is observable from 100 hPa to about 10 hPa.

In order to determine to what extent tropical 100 hPa temperatures control tropical and subtropical water vapor we calculated the correlation of the daily zonal mean water vapor and the daily 100 hPa tropical zonal mean temperature (8° S to 8° N). The calculation was made for the latitudes 40° S to 40° N at each pressure level from the upper troposphere to the mid stratosphere using Aura/MLS H_2O and NCEP T time series from August 2004 (start of Aura/MLS) to February 2011.

Since water vapor is transported upward and poleward from the tropics by the Brewer-Dobson circulation (BDC) we expect H_2O to be lagged in phase with tropical

ACPD
11, 25037–25061, 2011

100 hPa temperatures at higher altitudes and higher latitudes. On account of this transport we determine the time lag (in weeks) in order to find the maximum correlation of tropical T and H_2O.

The left plot in Fig. 1 shows the maximum correlation of zonal mean water vapor and tropical 100 hPa temperatures between 150 hPa and 20 hPa as a function of time lag displayed in the left plot. There is high correlation inside the tropics up to 20 hPa due to the rising water vapor (atmospheric tape recorder). The time lag is between 1 and 21 weeks from 100 hPa (~ 16.4 km) to 56 hPa (~ 20.1 km) which corresponds to an average vertical ascent rate of about 0.3 mm s^{-1}, which is similar to results obtained by Schoeberl et al. (2008). Poleward transport is much faster and happens over a few weeks. The time lag at 40° N and 100 hPa is 7 weeks whilst the time lag at the same pressure level at 40° S is 14 weeks which means that transport toward the Southern Hemisphere is slower. This is in agreement with the known characteristics of the BDC and the tropical pipe (Plumb, 1996). The correlation decreases with altitude and latitude because of mixing with other air masses and in situ water vapor production by the oxidation of methane (CH_4). It is interesting to see that the tropical water vapor at 121 hPa has no correlation to the 100 hPa temperature which suggests that the 100 hPa temperature is not controlled from below.

But the main result here is that the 100 hPa tropical temperature determines a large portion of lower stratospheric water vapor and its signal is carried upward and poleward with the characteristic time scales of the BDC. Randel et al. (2004) found a maximum correlation coefficient of 0.73 using UARS/HALOE water vapor and NCEP temperatures at 100 hPa. In this study the maximum value is 0.94. Aura/MLS data have a more uniform sampling than HALOE (HALOE took about 1 month to sample 1 latitude band compared to 1 day for MLS), which may explain the higher MLS correlation coefficients.

3.2 Seasonal cycle of water vapor and cirrus clouds

It is important to quantify how much seasonal cycle of water vapor in the TTL is due to a varying supply from below or due to regulation by local temperature. In order to

ACPD
11, 25037–25061, 2011

answer this question we utilize CALIPSO cirrus cloud data. CALIPSO can detect thin and subvisible clouds in the TTL and lower stratosphere.

Figure 2 shows a composite map of CALIPSO cirrus cloud fraction (contours 5–40 %) and MLS water vapor (color 2.5–5 ppm vmr) at 100 hPa averaged over 5 yr of the NH winter months December, January and February (DJF) on the left and the NH summer months June, July and August (JJA) on the right. For DJF significant cloud cover is found over land (South America, Africa, Northern Australia) in the Inter Tropical Convegence Zone (ITCZ) and over the maritime continent (Indonesia) and the Tropical West Pacific (TWP). The TWP pacific is known for its coldest tropopause and supposed to be the region where water vapor is freeze-dried to the lowest values according to saturation vapor pressure before it eventually enters the stratosphere through slow ascent (Gettelman et al., 2002; Fueglistaler et al., 2009). This region corresponds also to the lowest TTL water vapor values (dark blue ~2.5 ppm).

The JJA map on the right of Fig. 2 shows much higher water vapor values in the tropics (please notice the different color scale 3.5–6 ppm vmr) and especially in the subtropical monsoon regions over Asia and America. This is the source region of high water vapor values which are later distributed over the globe and eventually enter the stratosphere visible as ascending branch of high H_2O in the atmospheric tape recorder (Mote et al., 1996). The higher temperatures lead to less cirrus cloud cover, except over Asia. This is likely due to an elevated tropopause. In JJA the tropopause over the Indian monsoon region is around 85 hPa (not shown here) hence the 100 hPa level is more influenced by convection therefore cloud cover and water vapor are both elevated.

The Brewer-Dobson circulation (BDC) distributes TTL water vapor from the tropics poleward into the lower stratosphere. This transport can be seen in a zonal mean water vapor time series on the 100 hPa level. Figure 3 shows the time series of monthly zonal mean water vapor and zonal mean cirrus cloud fraction at 100 hPa from 40° S to 40° N. Water vapor is shown in color from 2 ppm to 6 ppm volume mixing ratio whereas contours of 1, 6, 11 and 16 % are given for cloud fraction. Both quantities show a significant seasonal cycle with H_2O minima and cloud fraction maxima occurring in the

ACPD
11, 25037–25061, 2011

same season (DJF). Water vapor maxima can be found at about 25° N in October. H_2O is very low in 2008 and 2009 due to ENSO (La Niña) and QBO occurring in phase (Liang et al., 2011) which led to colder TTL temperatures associated with faster BDC upwelling. Significant cirrus cloud fraction is found up to 35° N whereas it ends at 25° S. The highest cirrus fraction occurs during winter when water vapor is low. The poleward transport of H_2O can be identified to be faster to the NH and slower to the SH (evident from the steeper bend of the surfaces of same color to the south).

3.3 Anticorrelation of water vapor and cirrus clouds

Figure 2 and 3 clearly suggest that cirrus cloud fraction and water vapor are anticorrelated. In order to quantify the relation between cirrus clouds and water vapor at 100 hPa we utilize cirrus ice water content (IWC), which is also measured by CALIPSO. IWC and cirrus cloud fraction are nearly perfectly correlated ($r = 0.99$) hence the results we show with IWC would be the same if cirrus cloud fraction would be used. However, IWC has a more useful meaning on the amount of water measured. Seasonal averages of 100 hPa water vapor and IWC are analyzed to derive their relationship in the TTL. The here covered 5 yr seasonal time series of H_2O and IWC consists of a total of 19 data points at each location which are used for deriving the correlation.

Figure 4 shows the correlation map of water vapor (H_2O) and ice (IWC) at 100 hPa. The coefficients are close to −1 inside the tropics over land as well as over ocean. However the anticorrelation is higher over Indonesia and the Pacific Ocean than over South America. The correlation is positive outside the tropics in the NH. This is due to the elevated tropopause during the monsoon season, where the positive correlation reflects tropical tropospheric air. For this reason we leave out latitudes north of 8° N and define three regions for the TTL analysis. The dashed boxes in Fig. 4 highlight the defined regions Indonesia, Africa and South America.

An increase in TTL temperatures increases H_2O but decreases IWC. It is important to know the balance of water vapor and ice. In order to investigate this balance we analyze the amounts of H_2O and IWC at 100 hPa and try to find a linear relation. IWC

ACPD
11, 25037–25061, 2011

is given in units of mg m^{-3} and water vapor (H_2O) in parts per million (ppm) volume mixing ratio (vmr). At 100 hPa 1 ppm of water vapor corresponds to approximately 0.1 mg m^{-3} of ice (using the ideal gas equation and mean T of 195 K for the TTL).

Figure 5 shows scatter plots of tropical H_2O and IWC at 100 hPa. The investigated regions are the entire Tropics, Indonesia, Africa and South America as highlighted in Fig. 4 (Tropics: zonal mean 8° S–8° N, Indonesia: 12° S–8° N, 100° E–170° E, Africa: 8° S–8° N, 8° W–24° E, South America: 8° S–8° N, 80° W–50° W). Seasonal H_2O and IWC data are taken and averaged longitudinally and latitudinally in each domain. The linear regression equation is added in each Figure where the anticorrelation is clearly evident. The slopes are between −0.05 for the tropical zonal mean and −0.11 for Indonesia. Hence the range of slopes encloses the theoretical vapor to ice conversion factor of −0.1 according to which freezing of 1 ppm H_2O results in 0.1 mg m^{-3} ice. The slope for Indonesia (−0.11) is closest to the theoretical one and might also be the best representative, since this is the region of highest cirrus cloud occurrence throughout the year. Hence time periods of no IWC are rare and do not affect the seasonal averages. The slope for the tropical mean is lower because there are regions with much less IWC and hence the average is lower. These data clearly suggest that total water stays constant at 100 hPa in the ITCZ and that the temperature determines the partitioning between cirrus clouds (IWC) and water vapor.

The correlation coefficients of temperature and water vapor (T, H_2O), temperature and ice water content (T, IWC), water vapor and ice water content (H_2O, IWC) as well as the slopes ($m_{H_2O,IWC}$) of the regression lines of Fig. 5 and their uncertainties ($\Delta m_{H_2O,IWC}$) are summarized in Table 1. The tabulated correlation of H_2O and IWC does not represent the average of the correlation coefficients shown in Fig. 4 but the correlation was calculated with the averages of H_2O and IWC in each region instead. The first and second column show that H_2O and IWC are highly anticorrelated and correlated with temperature, respectively. Our hypothesis of total water conservation at 100 hPa is supported by observations over Indonesia where the correlation coefficients are highest and the slope $m_{H_2O,IWC}$ is closest to the theoretical −0.1.

4 Discussion

We showed in Fig. 1 that tropical 100 hPa temperatures determine TTL and lower stratospheric water vapor (H_2O) and show high correlation with H_2O (~ 0.9) to midlatitudes and up to 20 hPa. The 100 hPa T is mainly controlled from above by variations in the BDC (cooler when strong BDC, warmer when weak BDC).

The temperature is also the key parameter which determines the partitioning of vapor and ice in the TTL. We anticipated that temperature acts as the regulator for the coherent water vapor and cloud variabilities by balancing the partition between water vapor and ice in cirrus clouds. A decrease in temperature increases the relative humidity which favors freezing. This hypothesis is supported by the correlation study of H_2O and IWC (Figs. 3 and 4). H_2O and IWC are highly anticorrelated inside the tropics with highest values over Indonesia where cirrus clouds are most abundant. Highest IWC values are directly linked to lowest H_2O values (in DJF). The linear regression line of seasonal IWC and H_2O over Indonesia (Fig. 5) furthermore strongly suggests that total water at 100 hPa remains constant. Hence water switches seasonally between ice and vapor. Thus the yearly decrease of about 2 ppm H_2O over Indonesia from JJA to DJF translates into an icrease of about 0.2 mg m^{-3} in IWC. This further supports that cirrus clouds to a large extent serve as a seasonal reservoir for TTL water vapor. In other words this study points up that the supply of water into the TTL, which is convection, does not have a strong seasonal cycle.

However there is no anticorrelation of H_2O and IWC in the NH monsoon regions (i.e. between $\sim 10°$ N and $\sim 20°$ N, 100 hPa, Fig. 4). This is due to the elevated tropopause which is around 85 hPa. Hence the analysed 100 hPa level is within the convection where H_2O and cloud fraction are both enhanced. For this reason we chose our domain of analysis south of 8° N. The anticorrelation of H_2O and IWC is a little smaller over South America (–0.6, Table 1). This is due to the absence of IWC at 100 hPa in JJA which deteriorates the correlation.

ACPD
11, 25037–25061, 2011

We also found that the region of highest correlation of water vapor and cirrus cloud fraction is generally away from the regions of highest cirrus cloud occurrence as seen in Fig. 6. White contours show the 5 yr average of cirrus cloud fraction. The data are normalized in each region and the contours show 60 % to 100 % of the maximum cirrus cloud fraction in each region. The same normalization is applied to the maximum anticorrelation of H_2O and IWC (from Fig. 4). The highest anticorrelation for South America and Indonesia (dark blue rectangles) is found off the center of maximum cirrus occurrence. Maximum correlation is almost symmetrically East and West of the center of maximum cirrus over Indonesia. Over Africa, we also find a region of high anticorrelation far off the center and off the coast whilst there is still some collocation in the center.

A plausible cause for the off-center correlation is that temperature could become more potent to steer ice sublimation and evaporation in the outflow regions of the ITCZ as shown by the drawing in Fig. 7. The correlation is higher at the wings of the main convective areas than in the center where temperatures might be too low such that a small increase in temperature is not sufficient to evaporate all the ice. Whilst in the outflow regions the air is in the vicinity of the saturation condition and a small change in temperature can induce a phase change from ice to vapor and vice-versa, resulting in a higher anticorrelation between water vapor and cirrus clouds. Thus water is more strongly controlled by temperature in the outflow regions. But even inside the main convective areas the correlation is about −0.75 which supports the hypothesis of conserved total water at 100 hPa. We will explore this idea in the future.

In sum decreased TTL temperatures reduce the amount of water vapor to favor the increase of cirrus clouds. The question is if this is also true for decadal temperature variations. The increase in stratospheric water vapor between the last two decades before the year 2000 is still not fully understood since it was accompanied by a cooling of the tropical tropopause (Rosenlof et al., 2001). Hurst et al. (2011) report on a 0.74 ppm increase in the layer 16–18 km over Boulder, Colorado (40° N, 105° W) in the period 1980–2000. Since the source of midlatitude water vapor is in the tropics

ACPD
11, 25037–25061, 2011

we speculate that there must have been as well an increase of a comparable amount in the tropics. If our result is valid for decadal variations then a decrease in cirrus cloud fraction or IWC would have occurred during the same time period. A gain of 0.74 ppm H_2O would roughly correspond to a loss of 0.074 mg m^{-3} IWC. We are not aware of any observations of TTL IWC from 1980 to 2000. But it would be interesting to study this change with model simulations for the observed surface temperature increase (Solomon et al., 2010) to reproduce and test the effect of reduced IWC in cirrus clouds.

Current general circulation models poorly represent the seasonal cycle of cirrus clouds and water vapor in the TTL. Our results suggest that the tropical 100 hPa tropopause temperature determines the balance between cirrus cloud ice and water vapor at 100 hPa so that total water stays roughly constant. The seasonal cycle of water vapor is clearly anticorrelated with the seasonal cycle of cirrus cloud cover. There are more cirrus clouds during DJF when water vapor is low. This is a feature that is not yet represented in the GMAO GEOS-5 model (Global Modeling and Assimilation Office Goddard Earth Observing System Model, Version 5). Jiang et al. (2010) showed that the model represents the seasonal cycle of water vapor at 100 hPa though the numbers disagree with Aura/MLS especially during JJA. But there is no clear anticorrelation with the modeled IWC. And there is also not enough IWC found in the SH tropics as suggested by CALIPSO data (Fig. 3). If this observed relationship is not well represented by model physics it will certainly add to already large uncertainty in climate predictions since TTL water vapor and cirrus clouds have significant and opposite effects on the Earth's radiation budget.

5 Conclusions

We calculated the correlation of Aura/MLS water vapor and NCEP temperature as well as water vapor and CALIPSO cirrus cloud fraction and IWC in the tropical tropopause layer. Water vapor in the TTL and lower stratosphere is determined by the tropical

ACPD
11, 25037–25061, 2011

100 hPa temperature and has a maximum correlation of 0.94. Water vapor is transported upward and poleward following the Brewer-Dobson circulation and remains highly correlated with tropical 100 hPa temperatures throughout the lower stratosphere from tropics to midlatitudes. The correlation of T and H_2O decreases rapidly above 20 hPa due to mixing with air masses from outside the TTL and local H_2O production by the oxidation of methane. The center of H_2O transport is located at about 20° N during JJA and at the Equator during DJF. High water vapor values are distributed during JJA due to the convection in the monsoon regions, which brings a lot of H_2O to 100 hPa as can be seen in Fig. 2. Poleward transport is faster than upward and also faster in the Northern Hemisphere.

Furthermore, we find a high anticorrelation of H_2O and cirrus cloud fraction at 100 hPa in the tropics. The anticorrelation of water vapor and cirrus ice water content ($r = -0.91$) suggests that total water is constant throughout the year and temperature determines the balance between water vapor and ice in cirrus clouds. This result puts emphasis on the fact that convection, which is the supplier of TTL water, has no strong seasonal cycle. A linear regression analysis of H_2O and IWC shows that the slope (in $[-0.11, -0.05]$) encloses the theoretical slope of -0.1 if vapor is fully condensed in ice at 100 hPa in the TTL. Hence the seasonal cycle of water vapor is mainly a manifestation of cirrus formation leaving the total water at 100 hPa roughly constant. So basically cirrus clouds serve as a reservoir for TTL water vapor.

Current general circulation models (e.g. GMAO GEOS-5) do not represent the anticorrelation of water vapor and ice in the TTL and need to be improved to capture this important balance correctly since cirrus and water vapor have opposite effects on global climate.

Further we find that the regions of highest anticorrelation are in the outflow regions of the main convective areas. The reason for this is supposed to be related to a different temperature which is closer to saturation in the outflow regions. This is subject of ongoing work.

ACPD
11, 25037–25061, 2011

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References

Brewer, A. W.: Evidence for a world circulation provided by measurements of helium and water vapor distribution in the stratosphere, Q. J. Roy. Meteor. Soc., 75, 351, doi:10.1002/qj.49707532603, 1949. 25041

Chae, J. H., Wu, D. L., Read, W. G., and Sherwood, S. C.: The role of tropical deep convective clouds on temperature, water vapor, and dehydration in the tropical tropopause layer (TTL), Atmos. Chem. Phys., 11, 3811–3821, doi:10.5194/acp-11-3811-2011, 2011. 25039

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., Vössing, 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. 25039

Dessler, A. E., Palm, S. P., Hart, W. D., and Spinhirne, J. D.: Tropopause-level thin cirrus coverage revealed by ICESat/Geoscience Laser Altimeter System, J. Geophys. Res., 111, D08203, doi:10.1029/2005JD006586, 2006. 25039

de F. Forster, P. M. and Shine, K. P.: Stratospheric water vapor changes as a possible contributor to observed stratospheric cooling, Geophys. Res. Lett., 26, 3309–3312, doi:10.1029/1999GL010487, 1999. 25038

Fueglistaler, S., Dessler, A.-E., Dunkerton, T.-J., Folkins, I., Fu, Q., and Mote, P.-W.: Tropical tropopause layer, Rev. Geophys., 47, 1004, doi:10.1029/2008RG000267, 2009. 25039, 25043

Garrett, T. J., Heymsfield, A. J., McGill, M. J., Ridley, B. A., Baumgardner, D. G., Bui, T. P., and Webster, C. R.: Convective generation of cirrus near the tropopause, J. Geophys. Res., 109, D21203, doi:10.1029/2004JD004952, 2004. 25039

Gettelman, A., Randel, W. J., Wu, F., and Massie, S. T.: Transport of water vapor in the tropical tropopause layer, Geophys. Res. Lett., 29, 1009, doi:10.1029/2001GL013818, 2002. 25043

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, 2007. 25039

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. 25047

Jensen, E. J., Pfister, L., Bui, T.-P., Lawson, P., and Baumgardner, D.: Ice nucleation and cloud microphysical properties in tropical tropopause layer cirrus, Atmos. Chem. Phys., 10, 1369–1384, doi:10.5194/acp-10-1369-2010, 2010. 25039

Jiang, J. H., Su, H., Pawson, S., Liu, H.-C., Read, W. G., Waters, J. W., Santee, M. L., Wu, D. L., Schwartz, M. J., Livesey, N. J., Lambert, A., Fuller, R. A., and Lee, J. N.: Five year (2004–2009) observations of upper tropospheric water vapor and cloud ice from MLS and comparisons with GEOS-5 analyses, J. Geophys. Res., 115, D15103, doi:10.1029/2009JD013256, 2010. 25048

Liang, C. K., Eldering, A., Gettelman, A., Tian, B., Wong, S., Fetzer, E. J., and Liou, K. N.: Record of tropical interannual variability of temperature and water vapor from a combined AIRS-MLS data sets, J. Geophys. Res., 116, D06103, doi:10.1029/2010JD014841, 2011. 25044

Mote, P. W., Rosenlof, K.-H., McIntyre, M.-E., Carr, E.-S. Gille, J.-C., Holton, J.-R., Kinnersley, J.-S., Pumphrey, H.-C., Russel III, J.-M., and Waters, J.-W.: An atmospheric tape recorder: the imprint of tropical tropopause temperatures on stratospheric water vapor, J. Geophys. Res., 101, 3989–4006, doi:10.1029/95JD03422, 1996. 25041, 25043

Plumb, R. A.: A “tropical pipe” model of stratospheric transport, J. Geophys. Res., 101, 3957–3972, doi:10.1029/95JD03002, 1996. 25042

Randel, W. J., Wu, F., Oltmans, S. J., Rosenlof, K., and Nedoluha, G. E.: Interannual changes of stratospheric water vapor and correlations with tropical tropopause temperatures, J. Atmos. Sci., 61, 2133–2148, doi:10.1175/1520-0469(2004)061h2133:ICOSWVi2.0.CO;2, 2004. 25039, 25042

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.,

Discussion Paper | Discussion Paper | Discussion Paper | Discussion Paper |

Manney, G. L., Pickett, H. M., Pumphrey, H. C., Rosenlof, K. H., Sabounchi, X., Santee, M. L., Schwartz, M. J., Snyder, W. V., Stek, P. C., Su, H., Takacs, L. L., Thurstans, R. P., Vömel, 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 H_2O and relative humidity with respect to ice validation, J. Geophys. Res., 112, D24S35, doi:10.1029/2007JD008752, 2007. 25040

Read, W. G., Schwartz, M. J., Lambert, A., Su, H., Livesey, N. J., Daffer, W. H., and Boone, C. D.: The roles of convection, extratropical mixing, and in-situ freeze-drying in the Tropical Tropopause Layer, Atmos. Chem. Phys., 8, 6051–6067, doi:10.5194/acp-8-6051-2008, 2008. 25039

Rosenlof, K. H., Oltmans, S.-J., Kley, D., Russel, J.-M., Chiou, E.-W., Chu, W.-P., Johnson, D.-G., Kelly, K.-K, Michelsen, H.-A., 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, doi:10.1029/2000GL012502, 2001. 25039, 25047

Schneider, T., O'Gorman, P.-A., and Levine, X.-J.: Water vapor and the dynamics of climate changes, Rev. Geophys., 8, RG3001, doi:10.1029/2009RG000302, 2010. 25038

Schoeberl, M. R., Douglass, A.-R., Stolarski, R.-S., Pawson, S., Strahan, S.-E., and Read, W.-G.: Comparison of lower stratospheric tropical mean vertical velocities, J. Geophys. Res., 113, 24109, doi:10.1029/2008JD010221, 2008. 25042

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(5970), 1219–1223, doi:10.1126/science.1182488, 2010. 25038, 25039, 25048

Wang, P.-H., Minnis, P., McCormick, M. P., Kent, G. S., and Skeens, K. M.: A 6-year climatology of cloud occurrence frequency from Stratospheric Aerosol and Gas Experiment II observations (1985–1990), J. Geophys. Res., 101, 29407–29430, doi:10.1029/96JD01780, 1996. 25039

Winker, D. M., Hunt, W. H., and McGill, M. J.: Initial performance assessment of CALIOP, Geophys. Res. Lett., 34, 19803, doi:10.1029/2007GL030135, 2007. 25040

Wu, D. L., Chae, J. H., Lambert, A., and Zhang, F. F.: Characteristics of CALIOP attenuated backscatter noise: implication for cloud/aerosol detection, Atmos. Chem. Phys., 11, 2641–2654, doi:10.5194/acp-11-2641-2011, 2011.

Yang, Q., Fu, Q., and Hu, Y.: Radiative impacts of clouds in the tropical tropopause layer, J. Geophys. Res., 115, D00H12, doi:10.1029/2009JD012393, 2010. 25040
25039

ACPD
11, 25037–25061, 2011

Correlation of cirrus, water vapor and temperature in TTL

T. Flury et al.

Table 1. Correlations of T, H_2O and ice water content (IWC) in different regions. Tropics (zonal mean 8° S–8° N), Indonesia (12° S–8° N, 100° E–180° E), Africa (8° S–8° N, 8° W–24° E), South America (8° S–8° N, 80° W–50° W). The first column shows that 100 hPa temperature and water vapor are highly correlated. T and IWC are highly anticorrelated with a smaller value over South America though. The third, fourth and fifth column show the correlation of H_2O and IWC, the slope of the regression line as shown in Fig. 5 as well as the 2σ uncertainty of the slope. The anticorrelation is high with lower values over South America. The slope in the selected regions is between −0.08 and −0.11 which is fairly close to the theoretically expected −0.1 if water transform totally from ice to vapor and back.

Region	T, H_2O	T, IWC	H_2O, IWC	$m_{H_2O,IWC}$	$\Delta m_{H_2O,IWC}$
Tropics	0.94	−0.91	−0.91	−0.053	0.006
Indonesia	0.95	−0.84	−0.81	−0.109	0.019
Africa	0.95	−0.85	−0.78	−0.080	0.016
South America	0.92	−0.68	−0.60	−0.080	0.026

ACPD
11, 25037–25061, 2011

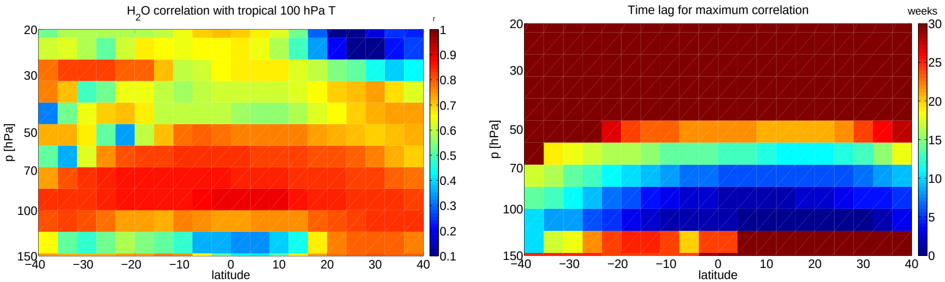

Fig. 1. Maximum correlation of NCEP tropical zonal mean 100 hPa temperatures (8° S–8° N) and MLS zonal mean water vapor at each latitude and pressure level on the left. Maximum correlation is found by shifting the water vapor time series by a certain time lag (in weeks) displayed in the right plot. The correlation is high ($r > 0.7$) throughout the lower stratosphere from Equator to midlatitudes. Upward and poleward transport can be identified by the increasing time lag in regions where r is still high. Poleward transport is faster than upward and also faster in the Northern Hemisphere.

ACPD
11, 25037–25061, 2011

T. Flury et al.

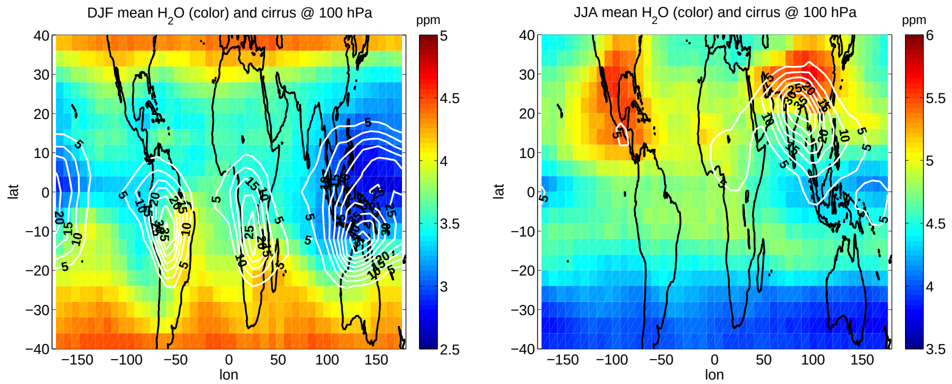

Fig. 2. Seasonal average of cirrus cloud fraction (contours) and water vapor (color) at 100 hPa in DJF (left) and JJA (right). Maximum cirrus cloud fraction occurs in DJF at the same time as minimum water vapor values, especially over Indonesia. During JJA water vapor is high and cirrus shift northward into the monsoon regions.

ACPD
11, 25037–25061, 2011

Correlation of cirrus, water vapor and temperature in TTL

T. Flury et al.

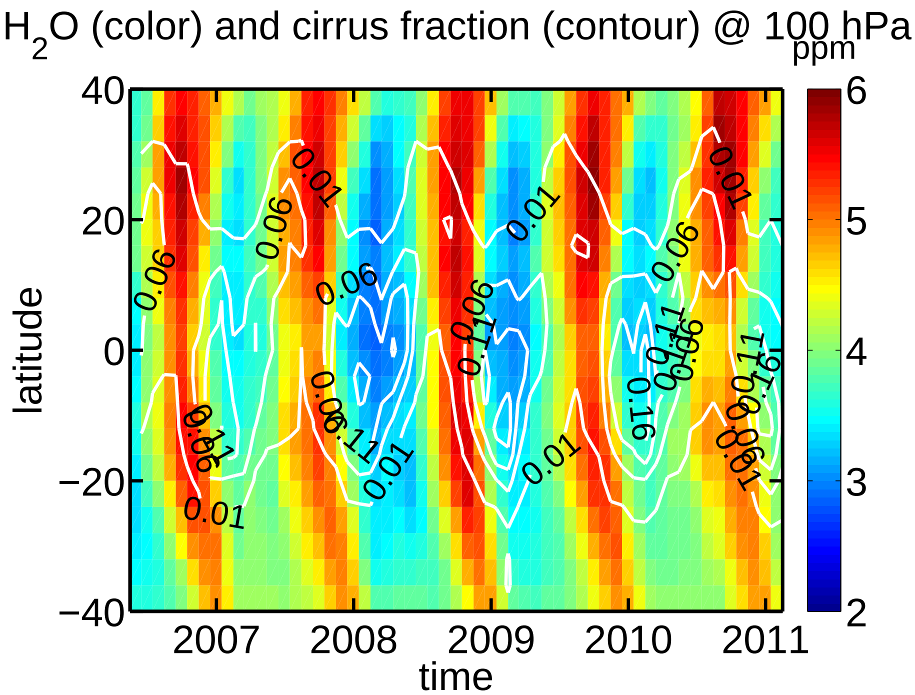

Fig. 3. Time series of zonal mean water vapor (color) and cirrus cloud fraction (contours) at 100 hPa displayed from 40° S–40° N. Poleward transport of high and low H_2O can be identified. Lower H_2O in 2008 and 2009 is due to ENSO-La Niña and QBO being in phase. Maximum cloud fraction occurs at the same period as minimum water vapor.

ACPD
11, 25037–25061, 2011

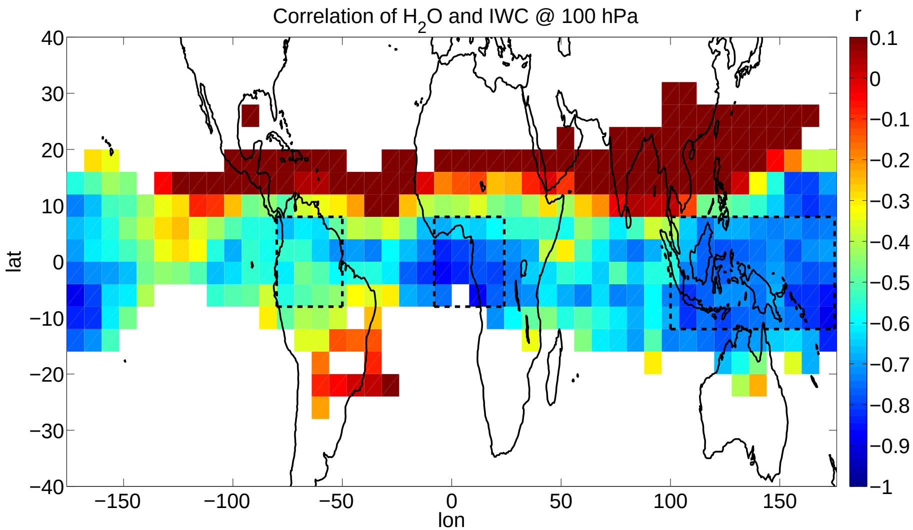

Fig. 4. Correlation map calculated with 19 seasonal data points of MLS water vapor and CALIPSO ice water content at 100 hPa. White areas indicate no IWC at 100 hPa. The anticorrelation is close to −1 over Indonesia and still high over Africa and South America. A band of high correlation (red) is found in the northern subtropics, Central America, India and East Asia. This is explained by the elevated tropopause during the monsoon season (Asian anticyclone). The dashed boxes are the regions of interest discussed in the text.

ACPD
11, 25037–25061, 2011

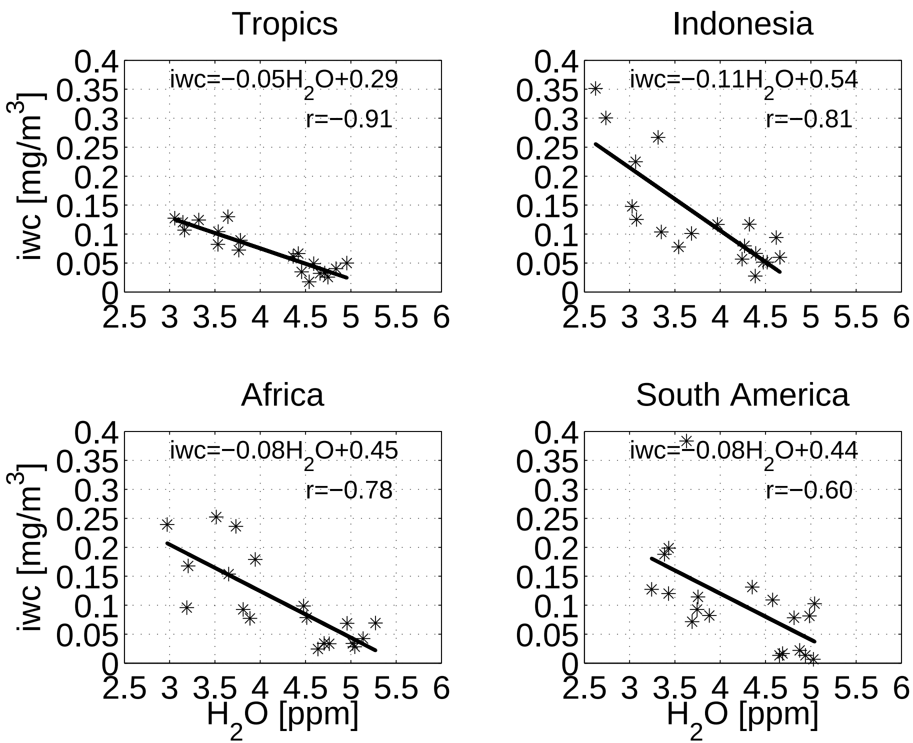

Fig. 5. Scatter plots of seasonal mean water vapor and IWC over the Tropics (8° S–8° N), Indonesia, Africa and South America at 100 hPa. A clear anticorrelation is visible. The regression line has a slope of approximately −0.1 which corresponds to the conversion factor of water vapor to ice in the TTL. 1 ppm vmr of water vapor transforms to approximately 0.1 mg m^{-3} of ice. These figures suggest that total water is roughly constant at 100 hPa in the tropics.

ACPD
11, 25037–25061, 2011

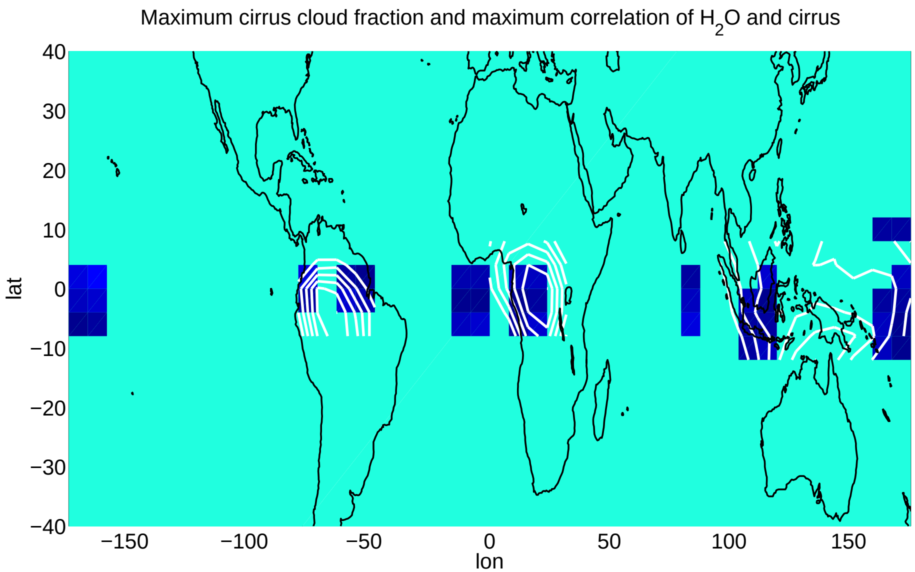

Fig. 6. Qualitative picture of the regions with maximum cirrus cloud fraction (contours) and maximum anticorrelation of water vapor and cirrus cloud fraction (dark blue rectangles). Data is averaged over the 5 yr period. The correlation is highest off the center of maximum cirrus occurrence. Over Indonesia the regions of maximum correlation are quite symmetrical around the center of maximum cirrus fraction. We suggest that water vapor is closer to saturation in the outflow regions and a small change in temperature can produce a phase change.

ACPD
11, 25037–25061, 2011

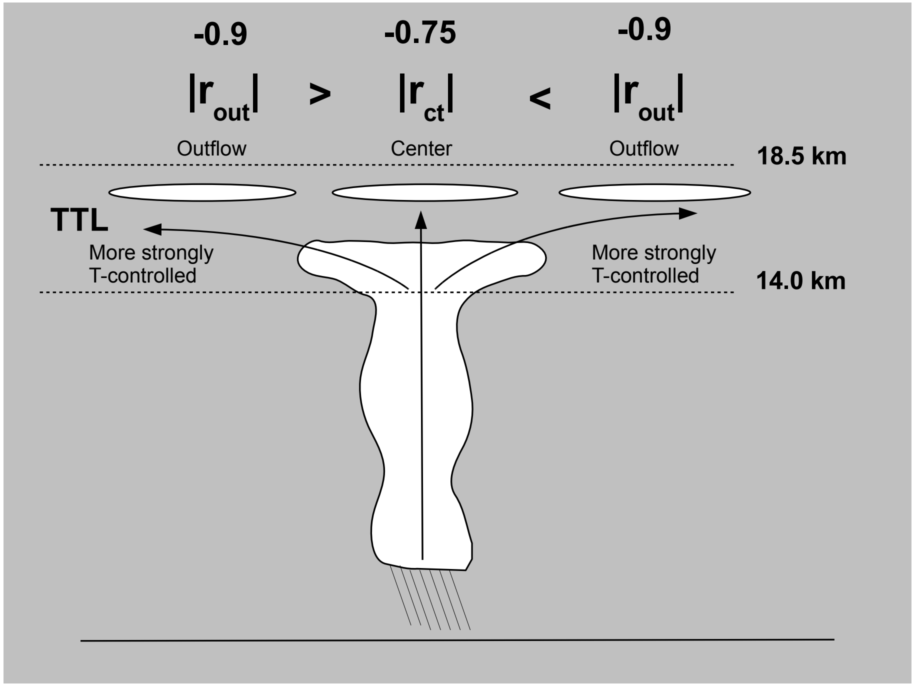

Fig. 7. Drawing of cumulus convection and cirrus formation (narrow clouds on top) inside the TTL. The anticorrelation (r) of water vapor and cirrus is higher in the outflow regions than it is in the center of the convective region ($|r_{out}| > |r_{ct}|$). Small changes of temperatures have a bigger effect on the state of water in the outflow regions therefore ice transforms to vapor and back hence the anticorrelation is high.

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