Tropical tropopause structure and processes as observed with GPS radio occultation.

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The vertical temperature structure of the tropical atmosphere has been explained as controlled by the combined effect of three green house gases: water vapor, carbon dioxide, and ozone. Absorption by water vapor of the light reflected off the Earth's surface would determine the temperature lapse rate in the lower troposphere up to the bottom of the Tropical Transition Layer (TTL); radiative absorption by carbon dioxide would dominate the temperature lapse rate between the bottom of the TTL and the coldest point in the upper-troposphere, the cold point tropopause (CPT), and; absorption of incoming solar radiation by ozone would control the temperature above the CPT. The TTL region can thus be very sensitive to changes in the relative abundances of these greenhouse gases. In this contribution we describe the seasonal evolution of temperature profiles in the TTL and their longitudinal structure using GPS radio occultation. The microwave character of the GPS signal permits this sounding to remain unaffected by clouds. The high vertical resolution of the GPS occultation data captures changes in TTL thickness already within the last few years which, according to the theory, would be reflecting recent changes in atmospheric CO_2 concentration. The correlation of this thickening with CPT temperatures anomalies and its possible impact on lower stratospheric water vapor is discussed as a function of time, season, and location.

I. Introduction

Water determines the radiative properties of the upper troposphere and lower stratosphere (UT/LS), whereby the increase of water observed since 1980 in the UT/LS may contribute as much to stratospheric cooling and tropospheric warming as a decrease in the concentration of stratospheric ozone.[1] Water also plays a central role in atmospheric chemistry. It is the major source of OH radicals, the major oxidizing species in the lower stratosphere, influencing the heterogeneous chemical reactions that destroy stratospheric ozone. Finally, water is a tracer in the UT/LS, and understanding how it enters the stratosphere contributes to our knowledge of how other chemical species are exchanged between the troposphere and the stratosphere.

The main source of lower stratospheric water is moist tropospheric air entering through the tropical tropopause.[2–4] Moist air cools down as it expands while rising rapidly from the lower troposphere into the top of the tropical convection layer. This top defines the secondary tropical tropopause (STT) which is the bottom of the tropical substratosphere, also called the tropical tropopause layer, or the tropical transition layer (TTL).[5] Within the TTL moist air typically starts a slower ascent still expanding and cooling down while water vapour continues to gradually condense, freeze, and precipitate to meet the local saturation mixing ratios. This dehydration process continues until air reaches a minimum saturation mixing ratio near the cold point tropopause (CPT), which is the coldest height at the UT/LS and defines the top of the TTL. The thermal structure of the TTL should thus be key to determining the processes by which water vapor crosses into the lower stratosphere.

One possible scenario for water vapor entering the stratosphere suggests that most air is processed above the Western Pacific, where the CPTs are coldest. For instance, longitudinal velocity of ascending air masses may lead them across the Western Pacific region where the coldest tropopause temperatures are found. Air

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would cool down and dehydrate in this region to values below the saturation values at the average CPT.[6] If no rehydration occurs, the Western Pacific rather than the local CPT, would determine stratospheric entry values of water. Radiosonde measurements in fact show the existence of undersaturated air crossing the tropopause,[7] but some problems with this scenario have also been noticed,[8] in particular the fact that there is a longitudinal structure in stratospheric water vapor. This suggests that not all water vapor that enters the lower stratosphere has crossed the same TTL regions. Other processes have also been observed such as convective overshoots,[9,10] supersaturated air entering the stratosphere,[7,11] or water vapor transport across the subtropical tropopause,[12] that can have an impact in water vapor transport accross the tropopause. While convective overshoots appear to be very infrequent[9] there are no global estimates of the relative importance of this against the other mechanisms. Last, the fact that an increase in stratospheric water was observed in the period 1980–2000[13] during which a cooling of the CPT was reported,[14,15] strengthens the case against the CPT temperatures as being the sole determinant of water vapor exchange across the tropopause. Water vapour exchange at the UT/LS is thus one of the most puzzling problems on the transport of tropospheric chemical species across the tropopause.

In this work we present temperature profiles inferred from GPS radio occultations captured by three satellites, GPS/MET, CHAMP, and SAC-C in the deep tropical region (15°S–15°N) to map the global thermal structure at the TTL. We address in particular how do satellite measurements add new scientific information to what is known from weather analyses. In the second section we discuss the occultation data used for our comparisons which started in April 1995 and continued for the years 1996, 2001, 2002 and 2003. In the third section we describe the interannual changes within the TTL, our finding that the maps of potential temperatures according to occultations and the ECMWF-TOGA weather analysis provide similar qualitative pictures, and how they suggest that air crossing the Western Pacific exits into warmer, possibly moister, regions before entering the stratosphere. The possible implications are sumarized in the conclusions.

II. Datasets

A. GPS radio occultation

GPS radio occultations are active limb soundings in which a receiver aboard a Low Earth Orbiter tracks the coherent signal broadcast by the Global Positioning System (GPS) satellites as they occult behind the Earth's atmosphere. GPS signals traversing the atmosphere are bent by the atmospheric density gradients across the ray path. This bending introduces a delay in the signal which can be measured. The delay rate of change can be used to calculate the atmospheric refractive index, n, or equivalently refractivity, $N \equiv (n-1) \times 10^{-6}$, as a function of height, z.[16,17] The GPS RO vertical resolution depends on the retrieval technique. Ray optics techniques are limited by the Fresnel diffraction limit, typically from 100 m in the lower troposphere to 1000 m in the lower stratosphere, with 200-300 km horizontal resolution.[17,18] This vertical resolution can be improved with wave optics techniques.[19] The data discussed here used ray optics retrievals, with resolution $\Delta z \sim$ 700–1000 m, and a sampling of $\sim$ 350 m, i.e. $\Delta p \sim 4$ hPa near the tropical CPT. This vertical resolution is higher than the 150hPa, 100hPa, 70hPa, and 50hPa pressure levels near the tropopause that are made available from the ECMWF analyses and reanalyses in the US.[20]

Occultation refractive index profiles can be used to extract temperature profiles with higher vertical resolution than any other satellite-based sounding technique, and up to altitudes of at least 32 km with a denser longitudinal coverage than radiosondes. The combination of vertical resolution and longitudinal coverage makes GPS RO especially valuable above the tropical oceans.

Here we compare a data record retrieved at JPL following procedures described in 18, 21 with profiles from ECMWF-TOGA, UCAR's semi-daily 22-level distribution of the 60-level ECMWF weather analysis.[20] As quality control of the occultation retrievals, we selected occultation refractivity profiles that were within 10% of the interpolated analysis at all heights below 32 km. Temperature differences were also required to be within 10 K at all heights between 32 km and the STT, and to show a mean absolute deviation of less than 5 K within the uppermost 10 occultation points (typically corresponding to the height range 35–41 km). These criteria select occultation and the analysis data that are consistent with each other, thus increasing the probability that they are correct.

B. Data validation

A discussion of the retrieval technique and limitations of GPS RO is given in 22. GPS/MET datasets have been validated previously for lapse-rate and cold point tropopause studies[23,24] where the data statistical first and second moments differed within less than 1 K from radiosondes. Paving the way for further improvements in retrieval strategies, the Danish Meteorological Institute, the GeoForschungsZentrum (GFZ), UCAR, and JPL are some of the centers currently retrieving occultation profiles. An intercomparison project among three of the centers has established that differences remain less than 1K. Temperature retrievals of GPS occultations have been validated against radiosondes to better than 1K standard deviation,[24–27] the ECMWF and NCEP analyses,[25–27] up to at least 25 km, and against other remote sensing instruments up to 40 km.[25] Agreement between coincident occultation captured by GPS RO receivers aboard different spacecraft is better than 0.6K.[28] Temperature fluctuations caused by gravity waves have also been validated against CRISTA.[29]

Figure (1) shows histograms of the differences between the GPS RO datasets used in this work and coincident radiosondes (RAOB) at five pressure levels in the tropical tropopause. RAOBS are considered coincident if they where launched less than 300 km and 3 hours from the occultation location. The RAOB temperatures where extrapolated linearly to the GPS RO location by using the local temperature gradients obtained from two reanalyses: NCEP in the left column, and ERA-40 on the right column. In both columns mean and median differences are below 0.5 K up to 50 hPa between RAOBs and GPS RO.

A further validation is presented in figures (2) between the GPS RO potential temperatures as a function of height and longitude against the potential temperatures obtained from the ECMWF-TOGA analysis when interpolated to the time and location of the occultation. The mean difference in potential temperatures ($\Delta\Theta \doteq \Theta_{occ} - \Theta_{ECMWF-TOGA}$) are shown in figures (2) within bins of size 0.5 km x 10 Degree as a function of month of the year. Only the data after 2000 have been considered. Dashed contours indicate negative differences and solid contours are for positive differences. Contours are spaced every 1 K, and annotated every 2 K. The lower thick green line marks the median STT height, and the upper green line marks the median CPT height as a function of longitude. It is seen that, except in the boreal summer, the largest positive differences accumulate immediately below the CPT with a tendency towards a higher potential temperature in the occultation data. The largest negative differences are found immediately above the STT.

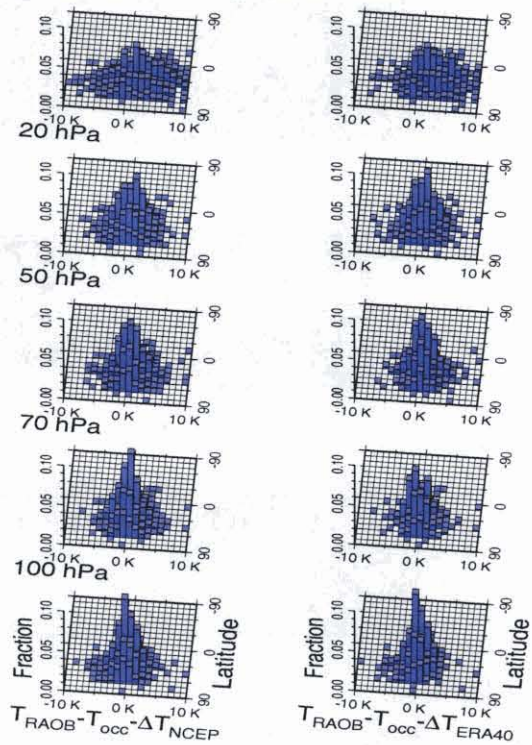


Figure 1. Histograms of the differences between the GPS RO used here and nearly coincident radiosondes at 150 hPa, 100 hPa, 70 hPa, 50 hPa, and 20 hPa. Left column: if the NCEP reanalysis temperature slope is used to interpolate the Radiosonde temperatures to the occultation location.Right column: if the ERA-40 reanalysis is used.

III. Results

A. Recent TTL evolution

The TTL is identified here as the layer between the minimum lapse rate in potential temperature, and the minimum temperature in the UT/LS.[5] A qualitative picture of the thermal structure near the TTL has been obtained from detailed radiative transfer calculations[30] and is given next.

Because the rate of change in the natural logarithm of potential temperature is proportional to the rate of entropy change, a change in the vertical gradient of potential temperature is associated with a change in the nature of the processes driving heat exchange, and hence entropy exchange, in the UT/LS. Below the TTL heat exchange processes are dominated by moist processes such as latent heat release from condensation, and the radiative effects of clouds. Above a certain height the water vapor content is small enough that the absorption of radiation by carbon dioxide and ozone take the dominant role in defining the temperature profiles. The calculations predict that if water vapor and carbon dioxide remained constant, increases in ozone should warm up the lower stratosphere, which would result in lowering the height of the cold point tropopause and a possible warming.[30,31] Holding water vapor and ozone constant, increases in carbon dioxide

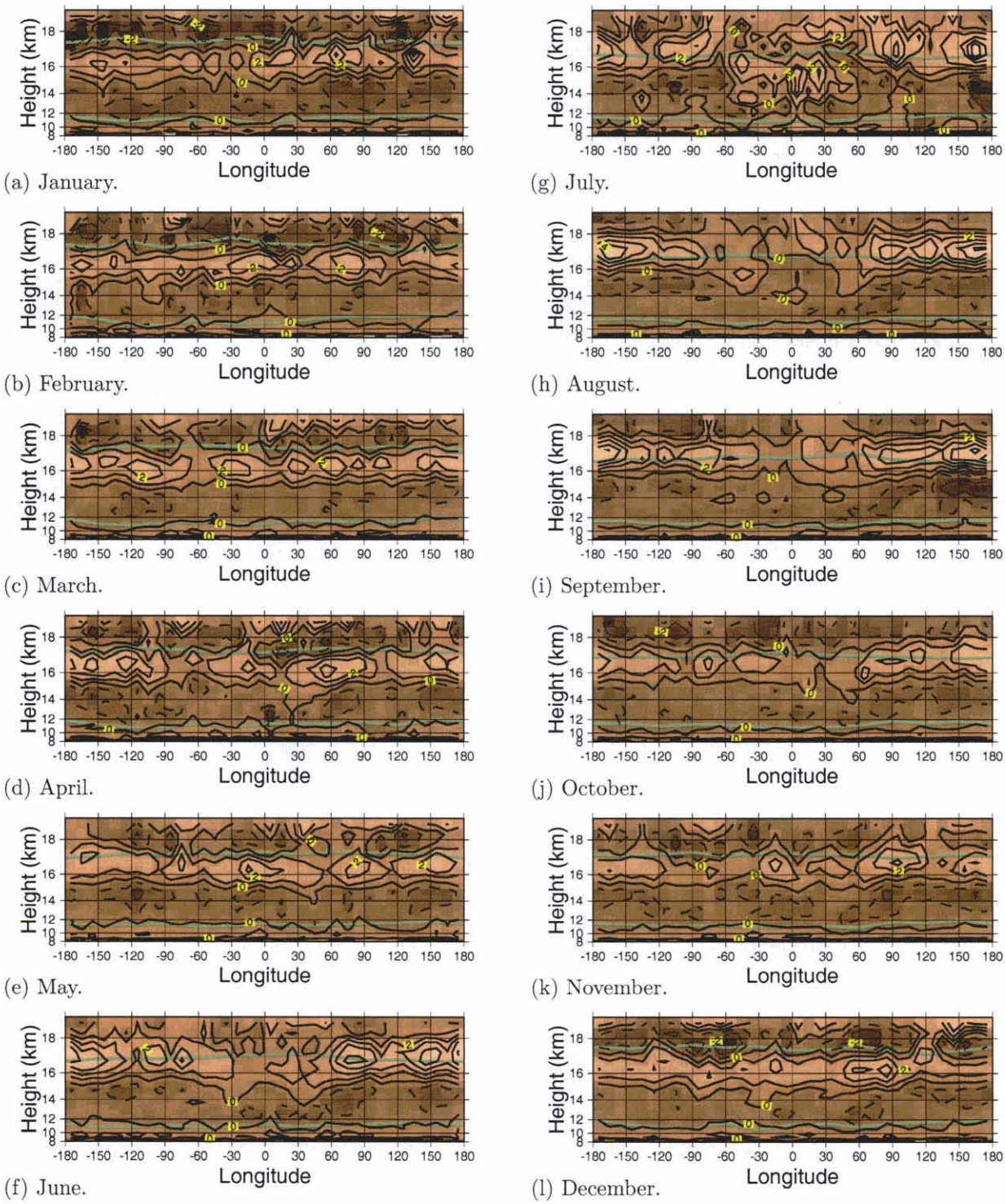


Figure 2. Seasonal cycle of the differences in potential temperature (occultation minus model) averaged over the 15°S and 15°N latitude range. Dark brown shows negative differences, light brown is for positive differences.

would lead to a larger lapse rate and thinning of the TTL, associated with a cooling of the CPT.

Table 1. Mean values and standard deviations (in parentheses) of the main thermodynamic variables at the TTL averaged over the 15°S and 15°N latitude range. The data used start in April 1995, stop in February 1997, and restart in June 2001.

Year*	CPT-Temperature	CPT-pressure	CPT-height	STT-Temperature	TTL-Thickness	TTL-Lapse-rate
			Occultations:			
1995*	193.15 (1.02)	95.76 (2.90)	16.91 (0.17)	228.36 (2.08)	5.55 (0.34)	6.29 (0.35)
1996	191.38 (1.61)	92.51 (2.60)	17.08 (0.15)	228.37 (4.30)	5.86 (0.70)	6.28 (0.43)
1997†	188.12 (2.67)	87.05 (4.64)	17.33 (0.28)	227.43 (10.78)	6.03 (1.42)	6.37 (0.45)
2001*	191.23 (1.13)	93.96 (1.20)	17.01 (0.07)	229.78 (1.38)	5.81 (0.30)	6.59 (0.29)
2002	191.33 (1.01)	92.84 (1.30)	17.11 (0.07)	229.45 (1.70)	5.81 (0.36)	6.51 (0.28)
2003	191.73 (1.02)	93.23 (1.40)	17.09 (0.08)	228.73 (1.64)	5.71 (0.34)	6.43 (0.28)
			ECMWF-TOGA:			
1995*	194.69 (1.13)	95.35 (2.18)	16.95 (0.13)	225.46 (2.99)	5.19 (0.43)	5.80 (0.38)
1996	192.20 (1.57)	89.34 (2.58)	17.31 (0.17)	226.89 (5.41)	5.75 (0.83)	5.96 (0.34)
1997†	189.77 (2.20)	86.50 (7.64)	17.47 (0.52)	223.17 (6.53)	5.45 (1.04)	6.15 (0.57)
2001*	191.75 (1.34)	94.82 (0.94)	16.96 (0.06)	222.10 (6.74)	4.78 (0.93)	6.23 (0.13)
2002	191.64 (1.37)	94.71 (0.63)	16.97 (0.03)	220.21 (5.47)	4.54 (0.78)	6.19 (0.20)
2003	191.87 (1.18)	94.82 (0.72)	16.96 (0.04)	220.58 (4.24)	4.61 (0.61)	6.13 (0.22)

* Coverage for this year missed the coldest CPT months. Temperatures have thus a warm bias.

† Coverage for this year missed the warmest CPT months. Temperatures have thus a cold bias.

Table 1 shows the evolution of the major TTL features within recent years, using only the occultations times and locations for both GPS RO and analysis. Apart from a small temperature bias, the CPT characteristics agree remarkably between occultation and the interpolated ECMWF-TOGA. A larger difference is seen in the STT characteristics. The characterization of the STT in the analysis dependes on the particular convective parameterizations of the model. The mean STT temperatures of ECMWF appear colder, and higher than in the occultations, thus leading to a thinner TTL with a smaller lapse-rate.

Focusing on the years with a complete data record, a slight thinning of the mean TTL, consistent with the observed recent increase in ozone and carbon dioxide.[32] The warming of the CPT temperature is consistent with the increase in ozone but, to first order, if carbon dioxide had remained constant, this warming should have led to a lowering of the CPT height, which is not observed. Both ozone, and carbon dioxide are known to have increased in recent years. The simultaneous slight increase in average lapse rate within the TTL while keeping a constant STT temperature, strongly suggests that GPS RO are detecting the effect of an increase in carbon dioxide on the thermal structure of the TTL.

This simple explanation assumes the global water vapor content to have remained nearly constant in the TTL. It has been argued that warming of the lower troposphere may contribute to increase its water content, but that the temperature at the top of the convection layer could remain constant.[33,34] This conjecture is consistent with the GPS RO measurements in table 1. There is a remarkable consistency in the mean temperature at the bottom of the TTL, despite the larger standard deviations of some years.

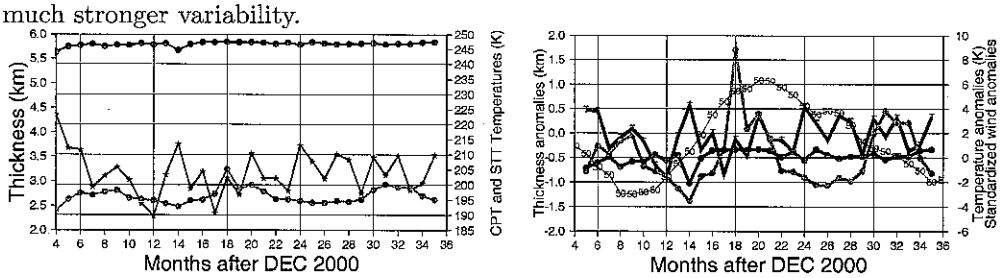
It is interesting to note a decrease in the standard deviation of the last GPS RO years (after 2000), while the mean STT temperatures remain within 229.0± 0.6 K throughout all the years with complete sampling, and 228.5± 1.1 K if the years with incomplete sampling are included. In contrast, the mean CPT temperature shows larger interannual fluctuations. While GPS RO increased their sampling in the new millenium, the same increase in number of profiles does not translate in a reduced standard deviation for the analysis. The standard deviation may be providing a measure of natural variability that is not within the focus of this work, but it is necessary to understand the reasons behind this decrease. Part of the reason for the high standard deviations in 1996 and 1997 can be justified: The data for 1997 were sampled during January and February the months with most natural variability at the tropics, and; in 1996 an encryption code was turned on the GPS signal which resulted in noisier retrievals.[21]

B. Interannual variability

The interannual variability of TTL thickness, and temperatures at its top and bottom are shown in figures (3). To minimize the effects of the clustered sampling nature of GPS RO, monthly averages were taken first in 30 degree longitudinal bins, and the average of these bins is shown in the figures for the months after April 2001. The anomalies, defined as the difference of each variable from its mean of the whole period, are shown

in figure 3(b). The anomalies show a remarkably constant mean temperature at the bottom of the TTL, while the CPT shows much stronger variability.

A biannual cycle is apparent in the CPT temperature anomalies. This cycle is reminiscent of the quasi-biennial-oscillation, which is known to affect Ozone concentrations. For that reason, the standardized zonal wind anomaly at 50 hPa is shown in light blue with the number 50. Except for June 2002, the local CPT maxima and minima correlate with TTL thickness maxima and minima during the cycles with negative wind anomalies, and anticorrelate for positive zonal wind anomalies. A seasonal (three-month) cycle also appears in the TTL thickness. During one phase of its biannual cycle the CPT temperature appears to be in phase with the TTL thickness, and in the other phase, it appears to be anticorrelated to the TTL thickness.



(a) Temperatures and thickness.

(b) Anomalies.

Figure 3. (a) Interannual variability of the TTL thickness (blue), temperature at the bottom (pink) and top (beige) of the TTL averaged over the 15°S and 15°N latitude range. (b) Interannual anomalies of TTL thickness (blue), and temperatures at the bottom (pink) and top (beige) of the TTL.

C. TTL Thermal structure as a function of longitude and height

One dehydration scenario for air entering from the troposphere into the stratosphere suggests that that air dehydrates as it crosses a cold TTL region (the "cold trap") along its largely horizontal trajectories with slow ascending velocity.[6] The importance of this possible scenario is partly strengthened by the paucity of convective flows penetrating into the TTL. Therefore transport of water vapor into the stratosphere is expected to be dominated by air parcels that follow nearly isentropic trajectories. The thermal structure of the TTL is addressed next in as far as it provides an insight into the isentropic trajectories that might be followed by air parcels cruising the TTL.

Latitudinally averaged contours of potential temperature from GPS RO data reflect the contour lines of isentropic surfaces. The locations at which these contours cross the CPT may be good markers of where does tropospheric air enter the lower stratosphere, and where does stratospheric air enter the upper troposphere. Isentropic levels are shown according to two independent datasets (ECMWF and GPS RO) in figures (4) and (5). In order to identify the robust features in both, median and mean heights of CPT and STT are plotted as green lines and green open squares respectively. The location of the local minima and maxima in potential temperature are common features which heightens the probability that they are real despite their fine scale structure (in fact a kriging contour technique, not shown, accentuates these maxima and minima even more). Such features may provide an insight into what is the origin of air entering the stratosphere.

One interesting feature is that the local minima in figures (4) and (5) within the lower TTL lie below the local maxima of the upper TTL and viceversa. Isentropes connecting local minima and maxima cross the CPT more deeply during the months of November through April. Air moving adiabatically would enter the troposphere from the stratosphere at the longitudes above the local maxima near the CPT. For instance, air cruising over the Western Pacific (90°–180°), which displays a local maximum below the CPT, will descend after exiting this region before it enters the stratosphere. This region is important because of its leading role in the cold trap hypothesis. The fact that air will subsequently subside after crossing this region increases the probability that it rehydrates before entering the stratosphere.

Upper tropospheric zonal winds are reported to follow a robust annual cycle of westerlies in boreal Summer, and easterlies from beginning of June to end of October.[35] This means that in the boreal Winter months, with larger longitudinal structure, air that has crossed the "cold trap" region enters into the Eastern Pacific region where it can be rehydrated prior to entering the Stratosphere over the American continent.

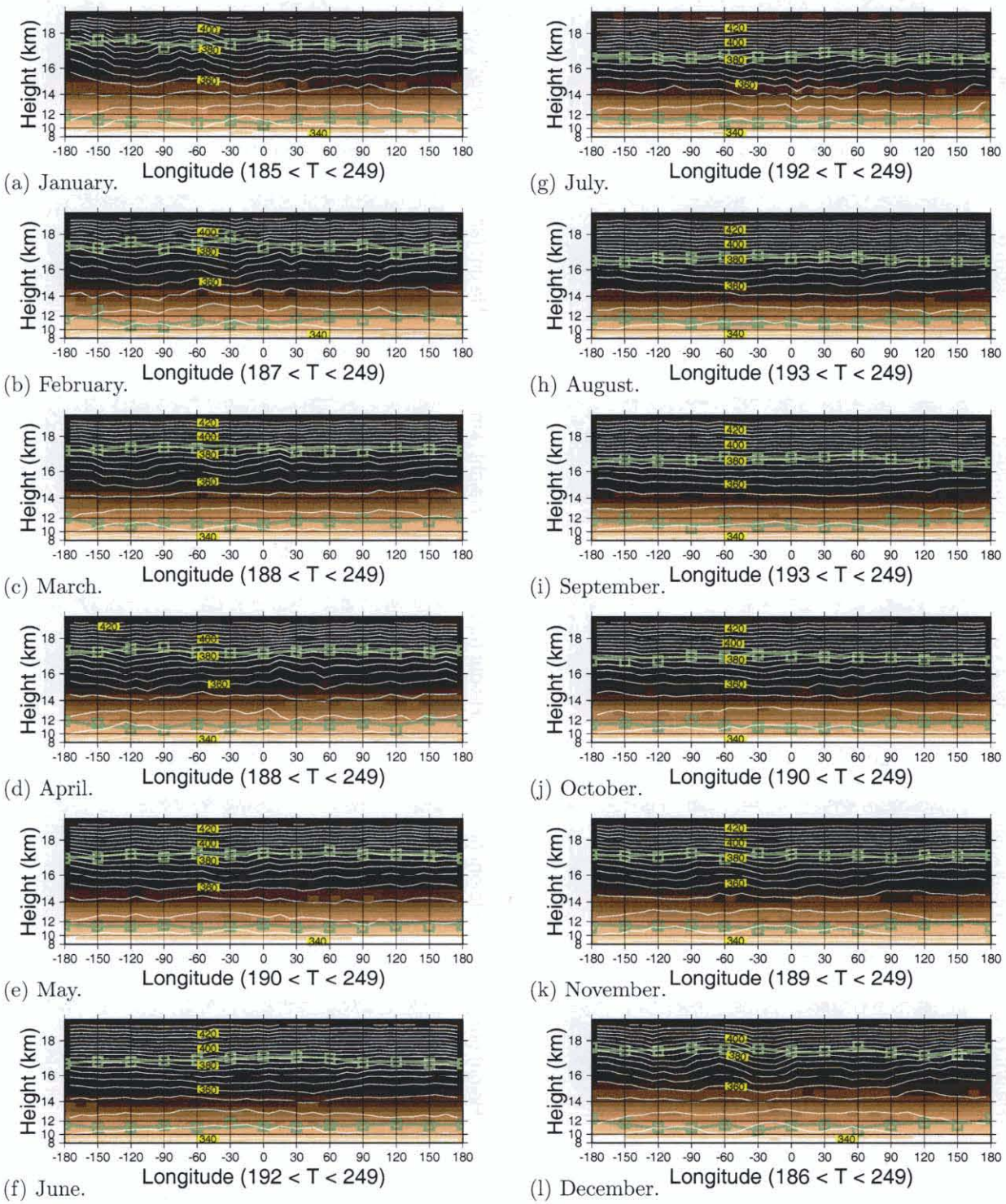


Figure 4. Seasonal cycle in the occultation potential temperature, STT, and CPT averaged over the 15°S and 15°N latitude range as a function of height according to GPS RO. The background shows the average within each bin of 0.5 km x 10 degree. Light brown is colder, dark brown is warmer.

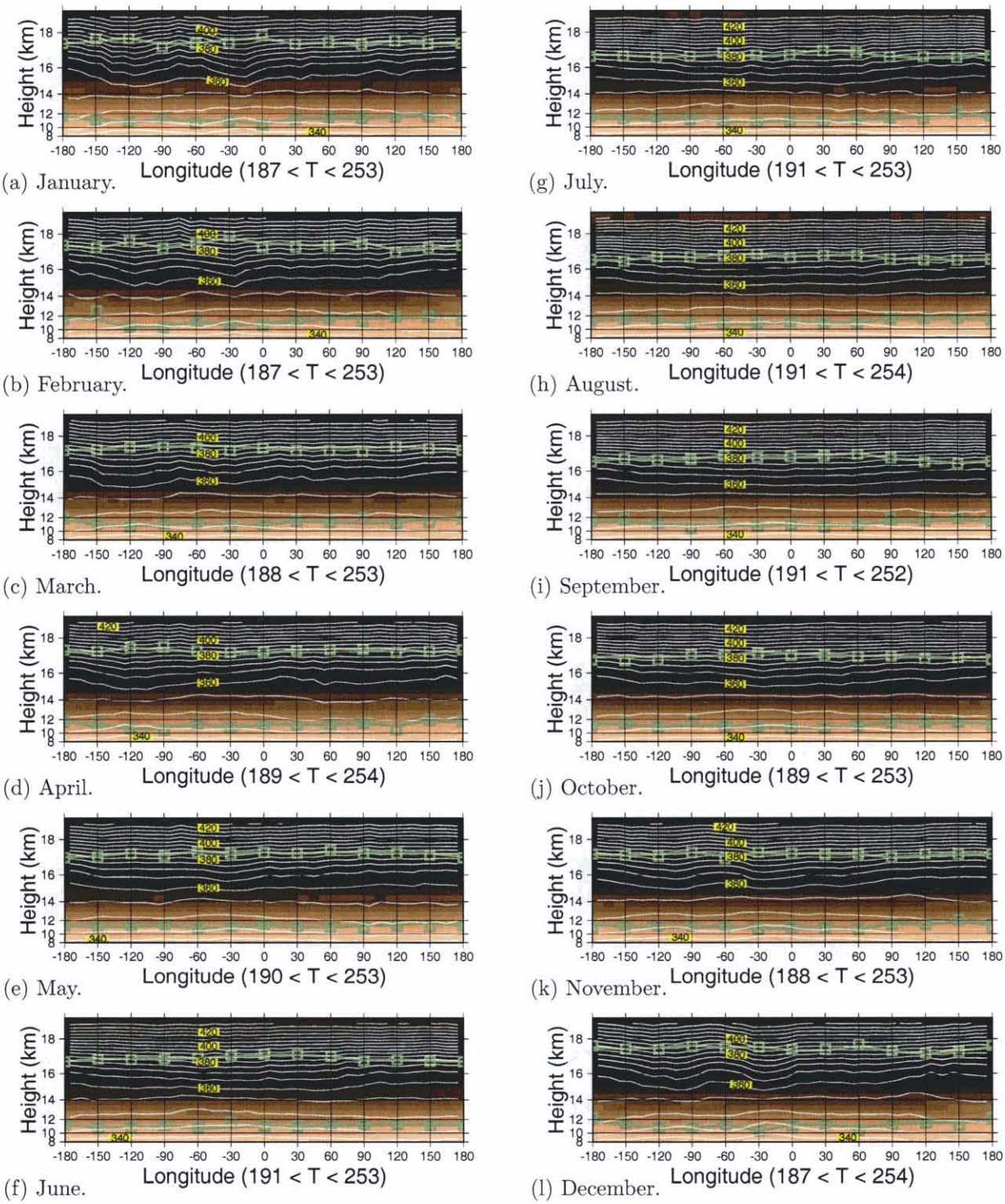


Figure 5. Seasonal cycle in the occultation potential temperature, STT, and CPT averaged over the 15°S and 15°N latitude range as a function of height according to ECMWF-TOGA. The background shows the average temperature (from the analysis) within each bin of 0.5 km x 10 degree. Light brown is colder, dark brown is warmer.

IV. Conclusions

According to GPS RO, a rising of the mean STT height while keeping the mean CPT height constant has lead to a slightly thinner TTL within recent years. This change in heights has been accompanied a nearly constant STT and CPT temperatures, leading to an increased lapse rate within the TTL. These observations altogether are consistent with with the ECMWF-TOGA analysis results, and the signature expected for an increase in Carbon Dioxide as has been reported for regional measurements.[32]

We also find that the Eastern Pacific region which has the coldest TTL temperatures and can strongly dehydrate the air, corresponds to a local maximum in potential temperature, such that air adiabatically cruising over this region will subsequently enter warmer and moister regions before entering the stratosphere. In the warmer regions, air is likely to mix with local moister air before entering the stratosphere, thus increasing the possibility of rehydration and decreasing the efficiency of dehydration by the cold trap region.

Acknowledgments

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References

[1]Forster, P. M. D. and Shine, K. P., "Stratospheric water vapour changes as a possible contributor to observed stratospheric cooling," *Geophys. Res. Lett.*, Vol. 26, No. 21, 1999, pp. 3309–3312.

[2]Brewer, A., "Evidence for a world circulation provided by the measurements of helium and water vapour distribution in the stratosphere," *Quart. J. of the Royal Meteor. Soc.*, Vol. 75, No. 326, 1949, pp. 351–363.

[3]Holton, J. R., Haynes, P. H., Mcintyre, M. E., Douglass, A. R., Rood, R. B., and Pfister, L., "Stratosphere-Troposphere exchange," *Reviews of Geophysics*, Vol. 33, No. 4, Nov 1995, pp. 403–439.

[4]Shepherd, T. G., "Issues in stratosphere-troposphere coupling," *J. of the Meteor. Soc. of Jap.*, Vol. 80, No. 4B, 2002, pp. 769–792.

[5]Gettelman, A. and Forster, P. M., "A climatology of the tropical tropopause layer," *J. of the Meteor. Soc. of Jap.*, Vol. 80, No. 4B, 2002, pp. 911–924.

[6]Holton, J. R. and Gettelman, A., "Horizontal transport and the dehydration of the stratosphere," *Geophys. Res. Lett.*, Vol. 28, 2001, pp. 2799–2802.

[7]Vömel, H. and Oltmans, S. J., "Comment on "A reexamination of the 'stratospheric fountain' hypothesis" by A. E. Dessler," *Geophys. Res. Lett.*, Vol. 26, No. 17, 1999, pp. 2737–2738.

[8]Haynes, P. and Shepherd, T., "Report on the SPARC/NASA Tropopause Workshop, Bad Tölz, Germany 17-21 April 2001," Tech. rep., World Meteorological Organization, 2001.

[9]Gettelman, A., Salby, M. L., and Sassi, F., "Distribution and influence of convection in the tropical tropopause region," *J. of Geophys. Res.*, Vol. 107, No. D10, 2002, pp. art. no. 4080.

[10]Alcala, C. M. and Dessler, A. E., "Observations of deep convection in the tropics using the Tropical Rainfall Measuring Mission (TRMM) precipitation radar," *J. of Geophys. Res.*, Vol. 107, No. D24, December 2002, pp. art. no 4792.

[11]Vömel, H., Oltmans, S. J., Johnson, B. J., Hasebe, F., Shiotani, M., Fujiwara, M., Nishi, N., Agama, M., Cornejo, J., Paredes, F., and Enriquez, H., "Balloon-borne observations of water vapor and ozone in the tropical upper troposphere and lower stratosphere," *J. of Geophys. Res.*, Vol. 107, No. D14, 2002, pp. art. no 4210.

[12]Bannister, R., O'Neill, A., Gregory, A., and Nissen, K., "The role of the south-east Asian Monsoon and other seasonal features in creating the 'tape-recorder' signal in the unified model," *Quart. J. of the Royal Meteor. Soc.*, Vol. 130, No. 599, 2004, pp. 1531–1554.

[13]Rosenlof, K. H., Oltmans, S. J., Kley, D., Russell, 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.*, Vol. 28, No. 7, 2001, pp. 1195–1198.

[14]Seidel, D. J., Ross, R. J., Angell, J. K., and Reid, G. C., "Climatological characteristics of the tropical tropopause as revealed by radiosondes," *J. of Geophys. Res.*, Vol. 106, No. D8, 2001, pp. 7857–7878.

[15]Zhou, X., Geller, M. A., and Zhang, M., "Cooling trend of the tropical cold point tropopause temperatures and its implications," *J. of Geophys. Res.*, Vol. 106, No. D2, 2001, pp. 1511–1522.

[16]Kursinski, E. R., Hajj, G. A., Bertiger, W. I., Leroy, S. S., Meehan, T. K., Romans, L. J., Schofield, J. T., McCleese, D. J., Melbourne, W. G., Thornton, C. L., Yunck, T. P., Eyre, J. R., and Nagatani, R. N., "Initial results of radio occultation observations of Earth's atmosphere using the global positioning system," *Science*, Vol. 271, No. 5252, February 1996, pp. 1107–1110.

[17]Kursinski, E. R., Hajj, G. A., Leroy, S. S., and Herman, B., "The GPS occultation technique," *Terrestrial Atmospheric and Oceanic Sciences*, Vol. 11, 2000, pp. 53–114.

[18]Hajj, G. A., Kursinski, E. R., Romans, L. J., Bertiger, W. I., and Leroy, S. S., "A technical description of atmospheric sounding by GPS occultation," *J. of Atmos. and Solar-Terr. Phys.*, Vol. 64, 2002, pp. 451–469.

[19]Gorbunov, M. E., "Canonical transform method for processing radio occultation data in the lower troposphere," *Radio Science*, Vol. 9, No. 5, 2002, pp. art no 1076.

[20]DSS-UCAR, http://dss.ucar.edu, 2004, ECMWF distributes its data to the US through NCAR. NCAR distributes it in the ECMWF-TOGA version which contains 22 pressure levels on a 2.5×2.5 degree horizontal grid projection of the full 60-level ECMWF analysis. We used the ds111.2 data set from NCAR's Data Support Section.

[21]de la Torre Juárez, M., Hajj, G. A., Kursinski, E. R., Mannucci, A. J., and Romans, L. J., "Single frequency processing of atmospheric radio occultations." *Int. J. of Remote Sensing*, Vol. 25, No. 18, September 2004, pp. 3731–3744.

[22]Ao, C. O., Hajj, G. A., Iijima, B. A., de la Torre Juárez, M., and Mannucci, A. J., "Remote Sensing of Fine-Scale Vertical Structures in the Atmosphere with GPS occultations," *This volume*, AIAA, 2004.

[23]Nishida, M., Shimizu, A., Tsuda, T., Rocken, C., and Ware, R. H., "Seasonal and longitudinal variations in the tropical tropopause observed with the GPS occultation technique (GPS/MET)," *J. of the Meteor. Soc. of Jap.*, Vol. 78, No. 6, 2000, pp. 691–700.

[24]Randel, W. J., Wu, F., and Rios, W. R., "Thermal variability of the tropical tropopause region derived from GPS/MET observations," *J. of Geophys. Res.*, Vol. 108, No. D1, 2003, pp. art. no. 4024.

[25]Rocken, C., Anthes, R., Exner, M., Hunt, D., Sokolovskiy, S., Ware, R. H., Gorbunov, M., Schreiner, W. S., Feng, D., Herman, B., Kuo, Y.-H., and Zou, X., "Analysis and validation of GPS/MET data in the neutral atmosphere," *J. of Geophys. Res.*, Vol. 102, 1997, pp. 29,849–29,866.

[26]Kursinski, E. R., Hajj, G. A., Schofield, J. T., Linfield, R. P., and Hardy, K. R., "Observing Earth's Atmosphere with Radio Occultation Measurements using the Global Positioning System," *J. Geophys. Res.*, Vol. 102, No. D19, 1997, pp. 23429–23465.

[27]Schmidt, T., Wickert, J., Beyerle, G., and Reigber, C., "Tropical tropopause parameters derived from GPS radio occultation measurements with CHAMP," *J. of Geophys. Res.*, Vol. 109, No. D13105, 2004, pp. doi:10.1029/2004JD004566.

[28]Hajj, G. A., Ao, C. O., Iijima, B. A., Kuang, D., Kursinski, E. R., Mannucci, A. J., Meehan, T. K., Romans, L. J., de la Torre Juárez, M., and Leroy, S. S., "CHAMP and SAC-C, Atmospheric Occultation Results and Intercomparisons." *J. of Geophys. Res.*, Vol. 109, 2004, pp. Art. no D06210.

[29]Preusse, P., Eckermann, S. D., and Offermann, D., "Comparison of Global Distributions of Zonal-Mean Gravity Wave Variance Inferred from Different Satellite Instruments." *Geophys. Res. Lett.*, Vol. 27, 2000, pp. 3877–3880.

[30]Thuburn, J. and Craig, G. C., "On the temperature structure of the tropical substratosphere," *J. of Geophys. Res.*, Vol. 107, No. D2, 2002, pp. art. no. 4017.

[31]Thuburn, J. and Craig, G. C., "Stratospheric influence on tropopause height: The radiative constraint," *J. of the Atmos. Sci.*, Vol. 57, 2000, pp. 17–28.

[32]Levinson, D. H. and Waple, A., "State of Climate in 2003," *Bul. Amer. Meteor. Soc.*, Vol. 85, No. 6, June 2004, pp. S1–S72.

[33]Hartmann, D. L., Moy, L. A., and Fu, Q., "Tropical Convection and the Energy Balance at the Top of the Atmosphere," *J. of Climate*, Vol. 14, 2001, pp. 4495–4511.

[34]Hartmann, D. L. and Larson, K., "An Important Constraint on Tropical Cloud-Climate Feedback," *Geophys. Res. Lett.*, Vol. 29, 2002, pp. art. no. 1951,12–1–4.

[35]Gage, K., McAfee, J., and Williams, C., "On the annual variation of tropospheric zonal winds observed above Christmas Island in the Central Equatorial Pacific," *J. Geophys. Res.*, Vol. 101, 1996, pp. 15061–15070.