New Characteristics of the Tropical Tropopause Revealed by CHAMP/GPS Measurements

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Abstract

Structure and variability of the tropical tropopause are presented using radio occultation measurements by CHAMP/GPS (CHAllenging Mini satellite Payload/Global Positioning System) from May 2001 to December 2004 (with a total of 175,149 occultations). The tropopause heights defined by both lapse rate and cold point generally show large-scale, off-equatorial maxima (tropopause increase at 20°N or S than at equator), and sometimes even a high tropopause for about 0.3 to 0.65 km (on an average) at 20°N and S simultaneously than at the equator along a particular meridian, in contrast to our previous knowledge. Although this feature has already been reported partially during the summer monsoon season, the present study shows the seasonal and geographical distributions of the tropical tropopause comprehensively using a new promising observational technique. In addition, the vertical shape of the tropopause is found to be sharp in the equatorial region and broad in the subtropics especially in northern winter. Possible mechanisms are discussed in light of dynamical and radiative processes.

1. Introduction

The tropopause region, which is the transition zone between the convectively mixed troposphere and the more stable stratosphere, has attained scientific interests because of its crucial role in the climate variability. A large number of studies has been carried out using various techniques (ground-based and satellite measurements and models) to characterize the properties of the tropopause across the globe (Randel et al. 2000, 2003 and references therein; Seidel et al. 2001; Zängl and Hoinka 2001). Long-term radiosonde and NCEP (National Center for Environmental Prediction) re-analysis data show a decreasing trend of the tropopause temperature in the tropics by 0.5 K/decade (Randel et al. 2000; Santer et al. 2003) and an increase in tropopause height of about 20 m/decade (Seidel et al. 2001).

In particular, the tropical tropopause region has long been highlighted from the viewpoint of the dehydration process of the air entering the stratosphere from the troposphere. Conventionally, the tropical tropopause was regarded as a sharp boundary between the troposphere and the stratosphere, but now it is recognized that there is a transition zone between the top of the convective region and the conventional tropopause, often called the Tropical Tropopause Layer (TTL) (e.g., Highwood and Hoskins 1998; Folkins et al. 1999; Gettelman and Forster 2002). Many studies are being carried out to clarify the dynamical, radiative, microphysical, and chemical processes that may control this layer.

However, due to the coarse vertical resolution of the global analysis data and the uneven distribution of radiosondes with gaps especially over tropical oceans, the comprehensive investigation of tropopause characteristics is still very difficult. As a new, promising tool to observe the tropopause characteristics, here we introduce the Global Positioning System (GPS) radio occultation data, which are well known for its high vertical resolution (~0.5 to 1 km near the tropopause) and global sampling (Wickert et al. 2005). The latter is particularly advantageous in the tropics, where radiosonde measurements are sparse. Moreover, radio occultation observations are calibration-free, thus have excellent long-term stability, and are insensitive to clouds and rain.

Recently, using the GPS/MET (GPS/METeorology satellite) and CHAMP/GPS (CHAlleging Mini satellite Payload/GPS) data, variability of the tropical tropopause was studied by Nishida et al. (2000), Randel et al. (2003), and Schmidt et al. (2004). They demonstrated the high accuracy of GPS temperature retrievals especially in the tropics. It is also reported that sub-seasonal variability of tropopause temperature and height is associated with gravity and Kelvin waves, and that significant correlations are found between these fluctuations and the convective activity (Randel et al. 2003; Randel and Wu 2005).

In this paper, characteristics of the tropical tropopause are further investigated using the CHAMP/GPS measurements. Results from previous studies using unevenly distributed radiosonde measurements (e.g., Seidel et al. 2001) showed that the tropopause height is highest in the equatorial latitudes and monotonically decrease from the tropics to subtropical latitudes (approximately '∩-shaped'). However, the tropical tropopause actually shows off-equatorial maxima (tropopause increase at 20°N or S than at equator), and sometimes even a high tropopause for about 0.5 to 0.8 km at 20°N and S simultaneously than at the equator along a particular meridian in a particular time period (Fig. 1). Hereafter we refer the former shape by case 'A' and later by case 'B' structure. Although this feature has already been reported partially using radiosonde data (Seidel et al. 2001), the present study investigates the seasonal and geographical distributions of the tropical tropopause comprehensively using the new promising observational technique.

2. Data base

The CHAMP/GPS satellite was launched on July 15, 2000 into an almost circular and near polar orbit (with the inclination of 87°) with an initial altitude of 454 km. See Reigber et al. (2005) for the system details. The first occultation measurement was performed on February 11, 2001, and since then about 150–200 occultations per day have been recorded. For the present study, we use the level 3 version 005 data from May 2001 to

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December 2004, which are produced by GeoForschungs-Zentrum (GFZ), Potsdam using their standard method for the Radio Occultation processing. See Wickert et al. (2005) for more details of the data analysis, its processing, initial results, and the validation. In comparison with radiosonde data, the temperature bias in the CHAMP/GPS data is less than 0.5 K (Schmidt et al. 2004). Although the height resolution varies from ~0.5 to 1 km near the tropical tropopause (at mid-latitudes it varies from 0.1 to 0.5 km), it has been interpolated to 200 m. For more details about the height resolution at various heights and latitudes, readers are to refer to Wicket et al. (2005). The latitudinal and longitude distribution of the radio occultations can be seen in Schmidt et al. (2004). Using CHAMP/GPS observations Schmidt et al. (2004) has presented the general characteristics of the tropical tropopause and its seasonal variation in more detail. However, they explicitly did not mention about these new features in their work.

The lapse rate tropopause (LRT) is defined according to WMO (1957), as "the lowest level at which the lapse rate decreases to 2°C/km or less, provided also the average lapse rate between this level and all higher levels within 2 km does not exceed 2°C/km." The cold point tropopause (CPT) is defined as the coldest temperature found in the vertical profile (below 20 km). The tropopause sharpness S_{TP} is defined as the change in vertical temperature gradient across the tropopause:

$$S_{TP} = \frac{T_{TP+\Delta Z} - T_{TP}}{\Delta Z} - \frac{T_{TP} - T_{TP+\Delta Z}}{\Delta Z},$$

with ΔZ = 1 km, where T_{TP} is CPT temperature and $T_{TP\pm\Delta Z}$ is the temperature at 1 km above (for +) and below (for −) CPT (Wirth 2000).

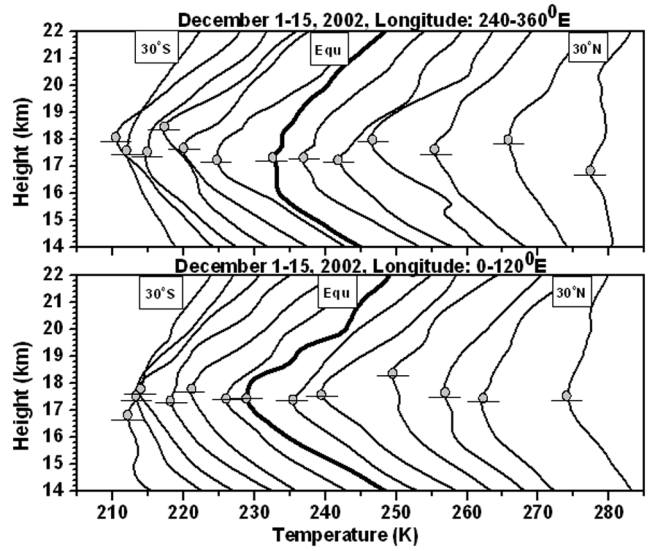

Fig. 1. Vertical profiles of temperature averaged at various latitudes from 30°S to 30°N by 5 degree (+/− 2.5 degree average) for 240°E−360° (top) and for 0120°E (bottom) during December 1−15, 2002. For each panel, the successive profiles from 30°S to 30°N are displaced by 5 K, and the profile with thick curve is for the equator. The locations of the cold point tropopause (circle) and of the lapse rate tropopause (bar) for each profile are indicated.

3. Results and discussion

3.1 Latitudinal variation

Figure 1 shows vertical profiles of temperature averaged at 30°N to 30°S by a 5 degree interval for 240 °E−360° and 0−120°E during December 1−15, 2002. Note that the tropopause height is estimated individually for each profile and then averaged for each latitude band of 5°. In the 240°E−360° longitude band, both LRT and CPT are at 17.2 km at the equator and located at higher altitudes (around 18 km) at higher latitudes (15−20°) in both hemispheres with difference in the tropopause height of about 0.8 km; the tropopause is seen as case 'B' structure along the meridian. In the 0−120°E longitude band, on the other hand, the tropopause height increases in northern hemisphere (NH) latitudes for about 0.7 km (around 15°N) but remains more or less constant in southern hemisphere (SH) latitudes (although slight increase of 0.3−0.4 km can be noticed); the tropopause has an off-equatorial maximum in NH (case 'A' structure). These features are revealed for the first time by using the GPS occultation data. In general, the tropopause height at particular longitude was thought to have a maximum altitude of about 17 km at the equator [e.g., Honika 1998; Santer et al. 2003] and to decrease towards the mid latitudes. Note that Seidel et al. (2001) has reported an off-equatorial maximum in the Asian monsoon region during NH summer months. Figure 1 shows that the off-equatorial maxima can also be seen over the south Indian Ocean and in the America-Atlantic section in NH winter.

Diurnal variations might affect the tropopause height and temperature for about 1.2 km and 20 K, respectively, as inferred by the MST radar (Revathy et al. 2001). In order to see this effect, we have also analyzed the day-night variation of the tropopause by selecting the radio occultations at 00 and 12 LT (local time) with ±3 hours. We confirmed that the off-equatorial maximum of the tropopause height is seen at both times (not shown).

It is noted that near the equator, there is not much difference in the tropopause height defined by lapse rate and cold point, but there exists slight difference in the sub-tropics. In the tropical latitudes the vertical shape of the tropopause is sharp, and it is broad at off-equatorial latitudes. This sharpness is closely related to the tropopause height and temperature variations with latitude; the tropopause is higher and colder when the tropopause structure is sharp, and vise versa. This feature is seen almost all the times irrespective of the season and will be shown more statistically in section 3.3.

Global operational/reanalysis data and most general circulation model (GCM) outputs cannot resolve this tropopause structure because of their coarse vertical resolution of more than 1 km. However, a GCM experiment with a 550-m resolution shows the case 'B' structure of tropical tropopause over the eastern Africa (Fujiwara and Takahashi 2001, Fig. 7). Therefore, this structure is probably one of the general characteristics formed by well-defined physical or dynamical processes. In the following sections, we show this feature more statistically with respect to season and longitude.

3.2 Seasonal variation

Figure 2 shows longitude-latitude sections of the cold point tropopause height, cold point temperature, and the outgoing long-wave radiation (OLR) during NH summer and NH winter averaged over the years 2001−2004. Small OLR regions are proxy for those with active convection in the tropics. The number of occultations used for the NH summer and winter amounts to 32,784 and 37,285, respectively. From the figure it is clear that the longitudinal variation is more evident in NH

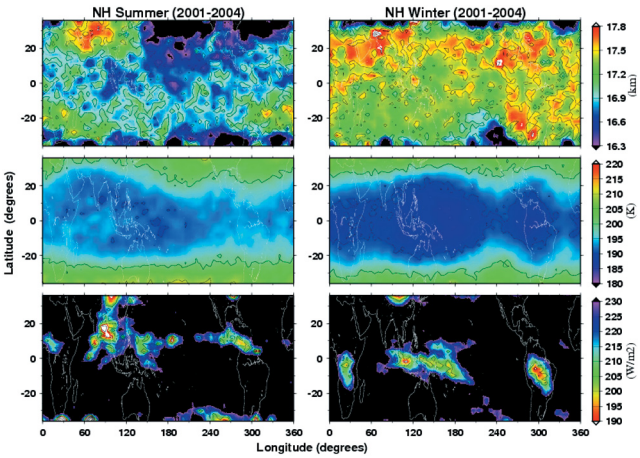

Fig. 2. Horizontal distributions of the cold point tropopause height (top), temperature (center), and the outgoing long-wave radiation (bottom) observed during NH summer (Jun-Jul-Aug) (left) and NH winter (Nov-Dec-Jan) (right) averaged over 2001–2004.

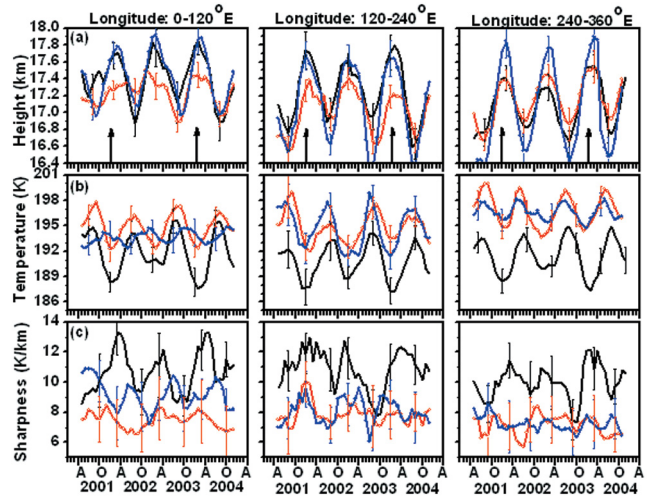

Fig. 3. Temporal variation of monthly averaged (a) height, (b) temperature of the cold point tropopause, and (c) tropopause sharpness (see text) observed at the equator (black), 20°N (blue, filled circle) and 20°S (red, open circle) at 0–120°E (left), 120–240°E (center), and 240°E–360° (panel) during May 2001–December 2004. The arrows in the top panels show the time when the QBO is in easterly phase at 20 km altitude.

summer than in NH winter. In general, the latitudinal and longitudinal characteristics can be roughly classified into three regions, namely 0–120°E (Africa to Indian Ocean), 120–240°E (Pacific Ocean), and 240°E–360° (America to the Atlantic). The case 'B' structure, i.e., off-equatorial maxima in both hemispheres, can be clearly seen at 0–120°E in NH summer and at 240°E–360° in NH winter. For the former, the tropopause is much higher around 20–30°N. In the Pacific region, the tropopause height increases from summer to winter hemispheres in both seasons. A very low tropopause region at 120°E–360° at 20–30°N in NH summer is noted.

In NH winter there is a large longitudinal variation in the tropopause temperature where minimum temperatures are found in the regions over Africa, western Pacific, and the northern part of South America. In NH summer around 0–120°E, it is known that the Asian monsoon circulation causes zonal asymmetry in the tropopause temperature and height (Randel et al. 2000).

The planetary-scale variability in the tropopause height is more prominently seen in NH summer, less prominent in NH winter, and least during the equinoxes (not shown). The tropical tropopause temperature in NH winter is on average about 5 K lower than in NH summer, and the height in NH summer is about 0.5 km higher than in NH winter. These results are consistent with previous studies (e.g., Reid and Gage 1981; Randel et al. 2000; Seidel et al. 2001). Figure 2 also reveals an interesting concurrence of lower and colder tropopause with active convection, e.g., over south-east Asia and the Bay of Bengal in NH summer and over Indonesia and South America in NH winter.

3.3 Monthly variation

More detailed characteristics of tropopause variability are investigated by separating the tropics into three regions mentioned above. Figure 3 shows the temporal variation of tropopause parameters at the equator, 20°N, and 20°S in the three regions, 0–120°E, 120–240°E, and 240–360°E from May 2001 to December 2004.

These three longitude bands are showing quite different features within the latitudes shown here. In the 0–120°E longitude band, in May–August of the years 2002 and 2004, there is clear enhancement in the tropopause height at subtropical latitudes (about 0.3–0.4 km on an average) with the lowest tropopause at the equator (case 'B' structure), but the highest tropopause at the equator (well known structure) is seen during other years (2001 and 2003). In NH winter months, the tropopause is lowest at 20°S and almost the same at the equator and 20°N. In the 120–240°E longitude band, more or less similar characteristics can be seen, but the tropopause height is lower than at 0–120°E throughout the year and particularly low in NH summer. The case 'B' structure is not seen during the observation period. In the 240–360°E longitude band, the amplitude of the height at 20°N is very large. The case 'B' structure is seen only during November 2002 to February 2003 (with difference of 04 to 0.5 km on an average).

The temperature variation shown in the plot reveals an anti-correlation with the tropopause height basically for all the longitude bands for all the season, except for the 20°N region at 0–120°E. The temperature is almost always lowest at the equator for all the three longitude bands, except for the 0–120°E band in NH summer where the 20°N region is the lowest.

The sharpness of the tropopause shown in the lower panels of Fig. 3 reveals that the sharpness is highest at the equator in all the longitude bands for most of the period. At the equator, it roughly shows an annual cycle with the maximum in NH winter. At 20°N and 20°S, the seasonality is not very clear for most of the longitude bands.

A signature of quasi-biennial oscillation (QBO) is evident. In the easterly phase of QBO at 20 km (in 2001–2002 winter and 2003–2004 winter), the height is slightly larger, the temperature is lower, and the sharpness is larger. The case 'B' structure observed in NH summer in 2002 and in 2004 at 0–120°E may be associated with the QBO westerly phase. Note that Randel et al. (2000) also noticed the QBO like variations using GPS/MET observations.

4. Summary and discussion

Using long term (44 months) temperature observations based on the GPS radio occultation measurements, we have found in general, that the latitudinal and longitudinal characteristics of the tropopause can be broadly classified into three regions, namely 0–120°E, 120–240° E, and 240°E–360°. The case 'B' structure, i.e., higher tropopause in subtropics, was clearly seen at 0–120°E in NH summer of 2002 and 2004, and also in NH winter of 2003 at 240°E – 360°. In the Pacific region, the tropopause height increases from summer to winter hemispheres. The tropopause tends to be lower over the active convective regions particularly over South East Asia and western pacific in NH summer and in Indonesia archipelago and South America in NH winter.

The tropopause height increases from the tropical to subtropical latitudes not only during Asian monsoon season/region which was reported in earlier studies (Seidel et al. 2001) but also during other seasons and longitudes. This is characterized as the vertical shape of the tropopause being sharp and getting broad away from the equatorial latitudes; the tropopause is higher and colder when the tropopause structure is sharp, and vice versa (Fig. 3c). Also, when the tropopause is highest, it is not necessarily coldest (Fig. 3b). In consistent with earlier reports, clear annual and QBO variations in the tropical tropopause are seen.

Dynamical and/or radiative processes may explain the observed behavior of the tropical tropopause. For the NH summer case especially over the Asian region, the summer monsoon circulation would greatly affect the tropopause, by enhancing the anti-cyclonic circulation in the upper troposphere (e.g., Dethof et al. 1999 and the reference therein). At the same time, active convection occurs over the region, and high anvil clouds may cover the bottom of the TTL. If we have such high, wide-spread clouds, long-wave heating from absorption by ozone will be diminished, and the lower stratosphere will become relatively cool (Norton 2001). This cooling will bring about the colder and lower tropopause with a sharp minimum. Numerical experiments using a radiative-convective model by Thuburn and Craig (2002) also pointed out the close relationship of the tropopause structure with the concentration of radiatively active gases (e.g., ozone) around the tropopause. Further studies are needed to quantify the contribution of these dynamical and radiative processes that may cause the observed variation of the tropical tropopause.

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