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Global distribution of *pauses* observed with satellite measurements

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Several studies have been carried out on the tropopause, stratopause, and mesopause (collectively termed as 'pauses') independently; however, all the pauses have not been studied together. We present global distribution of altitudes and temperatures of these pauses observed with long-term space borne high-resolution measurements of Global Positioning System (GPS) Radio Occultation (RO) and Sounding of the Atmosphere using Broadband Emission Radiometry (SABER) aboard Thermosphere-Ionosphere-Mesosphere Energetics and Dynamics (TIMED) satellite. Here we study the commonality and differences observed in the variability of all the pauses. We also examined how good other datasets will represent these features among (and in between) different satellite measurements, re-analysis, and model data. Hemispheric differences observed in all the pauses are also reported. In addition, we show that asymmetries between northern and southern hemispheres continue up to the mesopause. We analyze inter and intra-seasonal variations and long-term trends of these pauses at different latitudes. Finally, a new reference temperature profile is shown from the ground to 110 km for tropical, mid-latitudes, and polar latitudes for both northern and southern hemispheres.

1. Introduction

The earth's atmosphere is generally divided into different layers separated by the tropopause, stratopause, and mesopause, largely based on its thermal structure. Collectively, we refer them as the 'pauses'. In general, the altitudes of these pauses vary in both time and space (principally with latitude and season). Accurate knowledge of temporal and physical variations of these pauses is essential for understanding dynamical and chemical properties as they play very important roles in the middle atmosphere structure and dynamics.

The most accurate knowledge on the global variations of the tropopause has been obtained using radiosonde network (Gettelman *et al.* 2011 and references therein). However, the global distribution of the network of these radiosonde is inadequate to provide a comprehensive global picture, particularly over the large portion of the earth's surface covered by oceans. The recent availability of data from the Global Positioning System (GPS) radio occultation (RO) has introduced a new and valuable remote sensing tool for the earth's atmosphere (Kursinski *et al.* 1997). GPS RO enables precise profiles of refractivity and temperature to be determined with high vertical resolution (less than 1 km in the tropopause region). This technique requires no calibration, and is not affected by clouds, aerosols or precipitation. The occultation

Keywords. Tropopause; stratopause; mesopause; satellite measurements.

measurements are almost uniformly distributed over the globe. Several studies on the global and seasonal variation of tropopause were carried out (Ratnam *et al.* 2005; Añel *et al.* 2008; Schmidt *et al.* 2008; Son *et al.* 2011). In general, tropopause is the highest in the tropical regions, with gradual decrease towards the mid-latitude regions. The lowest altitudes of the tropopause occur at the polar latitudes.

Prior to the 1990's ground-based instruments, e.g., Rayleigh lidar, rocket observations are the only means of probing the region of stratopause and lower mesosphere (Kishore Kumar *et al.* 2008). Satellite observations have recently revolutionized the observations at these altitudes (see Ratnam *et al.* 2010 and references therein), however, there are relatively few reports available on the global distribution of the stratopause altitude. Perhaps this could be due to the weak seasonal variability over the globe, so that little attention has been paid to this matter. In general, the stratopause altitude varies between ∼45 and 50 km globally.

Relatively good amount of work on mesopause have been done using variety of optical sources across the globe (Ratnam *et al.* 2004). In recent years, variety of satellites allow monitoring of the thermal structure of the entire middle atmosphere including the tropopause, stratopause and the mesopause. Although the satellite measurements provide good global coverage, the vertical and temporal resolution is poor when compared to the ground-based measurements. In addition, the re-visiting timings of satellites in earlier days were limited to selected latitudes (see Kishore Kumar *et al.* 2008 for details). The Sounding of the Atmosphere using Broadband Emission Radiometry (SABER) aboard Thermosphere-Ionosphere-Mesosphere Energetics and Dynamics (TIMED) satellite is providing complete diurnal observations within 60 days over a fixed location and this data has been effectively used to study the global distribution of the mesopause (Ratnam *et al.* 2010) and the stratopause.

Until now, most of the studies concentrated in delineating the characteristics of these pauses independently, however, no report exists dealing all the pauses together. In the present study, for the first time, distribution of all the pauses observed near simultaneously using long-term satellite measurement is presented. Much attention is given to discuss the commonality and the differences among the pauses. It is also tested how different satellite measurements (Microwave Limb Sounder (MLS) on AURA mission, Atmospheric Infrared Sounder (AIRS) on AQUA mission, and High Resolution Dynamics Limb Sounder (HIRDLS)), re-analysis (Japanese 25-year reanalysis (JRA-25), European Center for Medium-Range Weather Forecasts Reanalysis (ERA)-Interim data, and United Kingdom Met Observation (UKMO)), and model (COSPAR international reference atmosphere (CIRA-86)) datasets compare each other. Finally, a reference temperature profile is provided for different latitudinal bands along with inter- and intra-seasonal variations and long-term trends.

2. Data and analysis procedure

For the present study, we mainly use GPS RO (Kursinski *et al.* 1997) data from both CHAllenging Mini Payload (CHAMP) (Wickert *et al.* 2001) processed by University Corporation for Atmospheric Research (UCAR) (2002–2007) and the Constellation Observing System for Meteorology Ionosphere and Climate (COSMIC)/Formosa Satellite 3 (FORMOSAT-3) (Anthes *et al.* 2008) processed by Taiwan Analysis Center for COSMIC (TAAC) data center (2006–2009), Taiwan, for detecting the tropopause. The height resolution of GPS RO varies from about 500 m in the troposphere to about 1 km in the lower stratosphere. We used SABER (Mertens *et al.* 2001) data (version 1.07) during 2002–2009 for the identification of stratopause and mesopause. SABER is a 10-channel radiometer that measures the infrared radiation from the earth's limb from approximately 20–120 km at every 58 s with ∼2 km resolution. The error in the temperature from GPS RO measurements is about 0.5 K near tropopause (Wickert *et al.* 2001; Jiang *et al.* 2004). The accuracy is around 1–2 K below 95 km and 4 K at 100 km in the SABER measurements (García-Comas *et al.* 2008).

In addition, we made use of several other datasets to assess the differences, if any, among (in between the) different datasets in detecting the various pauses. These additional datasets include data from other satellites like the AIRS on Aqua mission, the Earth Observing System (EOS) Microwave Limb, the HIRDLS measurements, the MLS on Aura mission, re-analysis datasets like the UKMO, ERA-Interim reanalysis, the JRA-25, and model outputs like CIRA-86. More details of these datasets, their global and altitude coverage, accuracy of measurements, basic principle used to obtain the data along with suitable reference are provided in table 1. It is important to note that the various datasets differ in horizontal and vertical resolutions. All the datasets are interpolated to uniform resolution. Though it would have been preferable to use radiosonde data for tropopause studies, we do not use these data because of its sparseness and possible inconsistencies amongst the data. On the other hand, the global reanalysis dataset is known to suffer a

Table 1. *List of various datasets used for the present study, its global coverage, altitude coverage, duration of observations considered, their accuracies, basic principle used to get the data and appropriate reference.*

Data base	Global data availability	Altitude coverage	Vertical resolution	Duration	Accuracy of temperature measurements			Basic principle	Reference
					Tropopause	Stratopause	Mesopause		
GPS RO	Global	10–55 km	∼0.5–1 km	2001–2009	0.5–1 K	NA	NA	RO	Kursinski *et al.* (1997)
SABER	Global	16–110 km	∼2 km	2002–2009	–	1–2 K	4–5 K	CO_2 radiances	Mertens *et al.* (2001)
AIRS_AQUA	Global	2–∼50 km	∼1–2 km	2002–2009	1–1.5 K	NA	NA	Infrared sounder	Aumann *et al.* (2003)
AURA_MLS	Global	9–∼95 km	∼3–4 km	2004–2009	1–2 K	2–3 K	3–4 K	Micro limb sounding	Waters *et al.* (2006)
HIRDLS	Global	10–∼50 km	∼0.5 km	2005–2007	1–2 K	NA	NA	Limb-scanning infrared radiometer	Gille *et al.* (2008)
UKMO	3.75° × 2.5°, 22 pressure levels	0.5 to ∼55 km	∼2–3 km	2002–2009	0.5 to ∼1 K	NA	NA	3D-Var data assimilation system	Lorenc *et al.* (2000)
ERA-Interim	1.5° × 1. 5°, 37 pressure levels, every 6 hours daily	0.1 to ∼48 km	∼2–3 km	2002–2009	1–1.5 K	NA	NA	4D-Var data assimilation system	Dee and Uppala (2009)
JRA-25	1.25° × 1.25°, 23 pressure levels, every 6 hours daily	0.1 to ∼55 km	∼2–3 km	2002–2009	<1 K	NA	NA	3D-Var data assimilation system	Onogi *et al.* (2007)
CIRA-86	2.5° × 2.5°, every 1 km, monthly	0 to 120 km	∼1 km	–	NA	NA	NA	Ground based and satellite measurements	Labitzke *et al.* (1985)

negative bias in tropical tropopause temperatures (Randel *et al.* 2000; Birner 2010), however, it is still adequate for investigating the spatial and temporal variability of the tropopause characteristics (Randel *et al.* 2000; Kiladis *et al.* 2001).

It is well known that the propagating atmospheric waves from gravity waves to planetary waves influence the temperature structures at any location. These wave effects can be minimized, though completely not removed, by averaging the data over a period sufficiently longer than the wave periodicity. Thus, the entire dataset (2002–2009) is divided into four seasons, namely spring equinox (March and April), summer (May–August), fall equinox (September and October), and winter (November–February) for northern hemisphere (NH), and seasonal averages of all the pauses are obtained. Averaged statistics of all the pauses were computed from individual temperature profile which forms the basis for all further investigations. Before that, each individual temperature profile from SABER is smoothed using low-pass filter with a cut-off wavelength of 2 km to remove the short scale gravity wave features. This exercise will make us to identify the stratopause and mesopause more precisely. Starting with the individual measurements, zonal means is determined for every 5° latitude bins. Tropopause is identified using WMO (1957, lapse rate) definition (i.e., 'the lowest level at which the lapse rate decreases to 2 K/km or less, provided also the average lapse rate between this level and all higher levels within 2 km does not exceed 2 K/km'.), stratopause altitude at the warmest point between 40 and 60 km, and mesopause altitude at the coldest point below 110 km. Note that sometimes stratopause altitude may go as high as 70 km particularly during the sudden stratospheric warmings (Hitchman *et al.* 1989; Manney *et al.* 2009). We also tested by keeping higher altitude limit as 70 km for the stratopause identification but could not see significant difference hence higher limit is kept as 60 km.

3. Results

3.1 *Zonal mean latitudinal variation of the pauses*

Figure 1 (also figure 2) depicts the climatological zonal mean values of temperature and altitudes of tropopause from GPS RO, CHAMP and COSMIC/FORMOSAT-3 measurements, stratopause and mesopause from SABER measurements obtained for NH winter and NH summer (spring equinox and fall equinox) seasons averaged over the period 2002–2009. The data points are averaged for 5° latitude and point is represented at the center of that latitude interval.

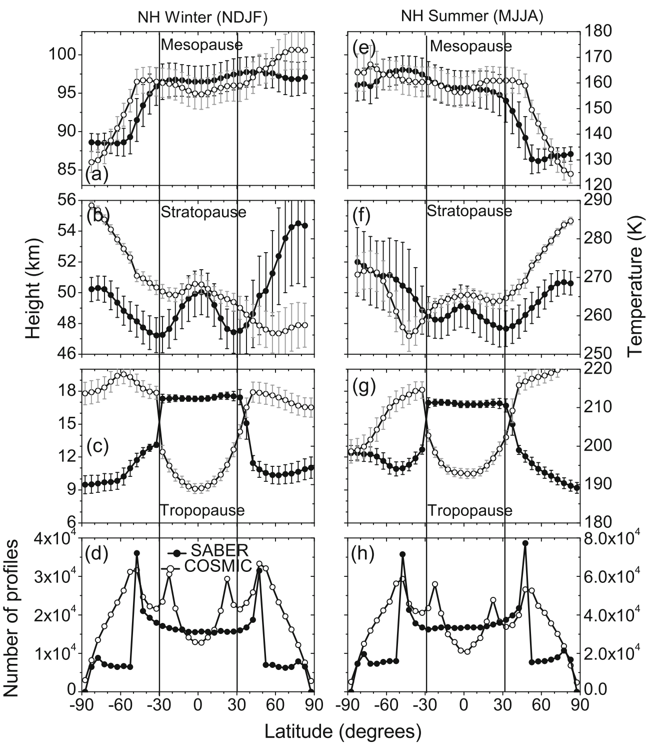

Figure 1. Zonal mean latitudinal variation of tropopause, stratopause and mesopause altitudes observed during NH winter (**a**–**c**), NH summer (**e**–**g**), seasons using GPS RO (tropopause) and SABER (stratopause and mesopause) measurements. Number of measurements used from both GPS RO and SABER for every 5° latitude during NH winter and NH summer is shown in (**d**) and (**h**), respectively.

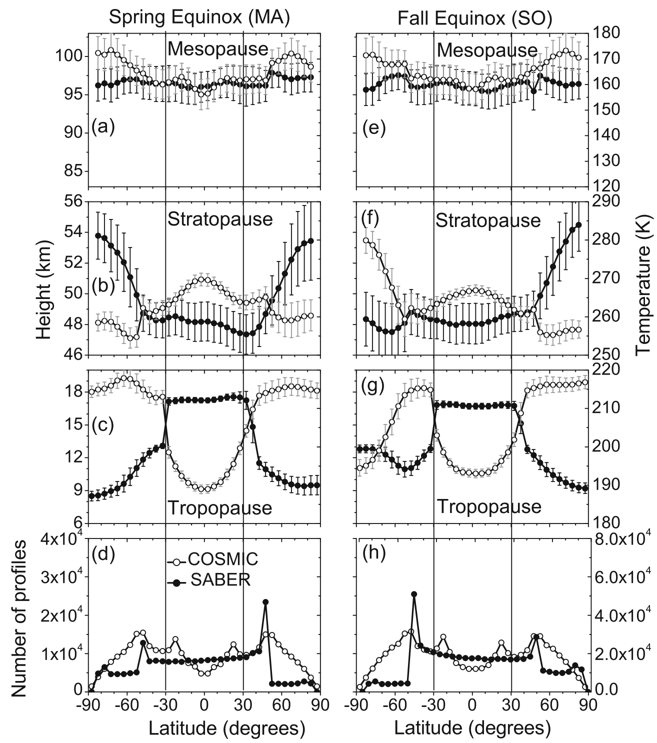

Figure 2. Same as figure 1 but for spring equinox (**a**–**c**) and fall equinox (**e**–**g**) seasons.

The general features of all the pauses are in agreement with the features presented in earlier works (Ratnam *et al.* 2010; Tomikawa *et al.* 2008; Santer *et al.* 2003).

Figure 1(d and h) (and figure 2d and h) shows the number of profiles used from both GPS RO (CHAMP+ COSMIC/FORMOSAT-3) and SABER for every 5° latitude bins for NH winter and NH summer (spring equinox and fall equinox), respectively. The zonal distribution of GPS RO shows a nearly symmetric behaviour between the NH and Southern Hemisphere (SH) with local maxima in the mid-latitudes and around 20°S and 20°N. Because of the GPS RO orbit geometry, the longitudinal occultation distribution is nearly constant (figure not shown) in the 5° bins from 0° to 360°E. The total number of high-resolution temperature profiles for GPS RO (SABER) in the time period from January 2002 (January 2002) to November 2009 (October 2009) is 2022842 (2944927). Note that there is drastic change in the number of profiles around 50° due to satellite geometry (Mertens *et al.* 2001) in SABER. The features observed between 80° and 90° in both the hemispheres may not be statistically significant due to the small number of profiles.

From figure 1 (also figure 2), it can be noticed that the tropopause has a strong latitudinal variation. The tropopause altitudes are nearly constant in tropics (30°S–30°N) and reach altitudes of about 17.3 km in the deep tropics (10°S–10°N) and they decrease to about 17.1 km at the margin of the tropics. The strongest gradients in tropopause altitude occur between 30° and 40° latitudes in both the hemispheres with mean altitudes decreasing to 9.7 km at southern polar latitudes, whereas in the northern polar region between 60° and 90°N, the tropopause altitude is nearly constant at about 10.5 km. The lowest mean tropopause temperatures are found in the deep tropics (2.5°–7.5°N) where they reach the temperature of 189.5 K. During NH winter, the mean temperature increases from the equatorial region to the subtropics and temperature decreases from the NH subtropics to the North Pole. The temperature shows a maximum ∼220 K at 50°–55°S, during NH winter. South of 55°, the seasonal mean temperature decreases to 200.74 K during NH summer. Though statistically not significant, at latitudes >70° we find large differences in tropopause temperatures during summer and winter and both equinoxes. This general climatology means the tropopause altitude and temperature are in good agreement with global tropopause parameters reported in previous studies (Schmidt *et al.* 2004, 2008; Añel *et al.* 2008; Son *et al.* 2011).

In topical latitudes, we observe a higher stratopause (∼50 km) which decreases towards the subtropics and reaches the lowest altitudes (47–48 km) near 30° in both the hemispheres, agreeing well with the results reported by Sivakumar *et al.* (2006). This feature is more pronounced in the NH winter than in the NH summer and it is less apparent in fall equinoxes. In the NH summer and winter, the stratopause altitudes increase at latitudes greater than 30° and reaches a maximum between 60° and 80° with a more pronounced peak in the winter. We observe significant differences in the equinoxes when compared to the NH summer and winter with small (almost flat) variations in the stratopause altitude around 48 km in the tropical latitudes. The stratopause temperature generally decreases from the summer pole towards the winter mid-latitudes, it is minimized at 30°–35° latitude in the winter hemisphere unlike CIRA-86 model (Labitzke *et al.* 1985) which showed the latitudinal minima of the stratopause temperature at 15°–30° latitude in the winter hemisphere (Beagley *et al.* 1997). The temperature distribution in the NH winter is mostly symmetric (similar variability) to the one of the NH summer. Similar latitudinal temperature minimum are also reported in a low-resolution (T32) GCM (Beagley *et al.* 1997). Beagley *et al.* (1997) showed that these latitudinal temperature minimum in the winter subtropics are accompanied by an easterly shear in the equatorward region, which will satisfy the thermal wind balance. These latitudinal temperature minimum at the wintertime subtropical stratopause have been captured by other satellite observations as well (e.g., Hitchman and Leovy 1986). This shows that the latitudinal temperature minimum is a robust feature at the subtropical stratopause in the winter hemisphere. Significant differences in the stratopause temperatures between spring and fall equinoxes are observed in the SH polar latitudes with high temperatures during fall equinoxes when compared to SH spring equinoxes.

During the NH winter season, the mesopause altitude is at ∼97.5 km throughout the NH and gradually decreases from equator to 30°S. At latitudes >30°S the mesopause altitude starts decreasing rapidly and reaches ∼88 km at 60°S with a temperature of ∼135 K. A mirror image of this pattern can be seen during the NH summer. The mesopause is again at a high level of ∼98 km from 80°S to 30°N with a temperature of ∼165 K. At latitudes higher than 30°N, the mesopause shifts to a lower level of ∼87.5 km with temperature of ∼130 K. During the spring and fall equinoxes, the mesopause is at ∼97 km altitude with temperatures of 160–170 K. The mesopause temperatures are slightly low at low latitudes compared to high

Table 2. *Descriptive statistics of all the pauses temperature and altitudes observed during different seasons for the time period of 2002–2009.*

	NH winter (NDJF)			Spring (MA)			NH summer (MJJA)			Fall (SO)		
	Min	Max	Range	Min	Max	Range	Min	Max	Range	Min	Max	Range
Mesopause												
Ht (km)	88.44	97.94	9.51 ± 0.60	95.75	97.82	2.07 ± 0.09	86.19	98.08	11.89 ± 0.71	95.43	97.55	2.12 ± 0.10
T (K)	129.17	172.96	43.79 ± 2.0	156.08	173.43	17.35 ± 0.85	124.56	167.13	42.56 ± 1.97	158.20	173.21	15.01 ± 0.75
Stratopause												
Ht (km)	47.53	52.27	4.74 ± 0.24	47.19	52.27	5.07 ± 0.26	47.59	52.47	4.89 ± 0.29	46.36	53.65	7.29 ± 0.30
T (K)	256.90	288.04	31.14 ± 1.55	260.31	274.32	14.01 ± 0.68	255.39	278.93	23.54 ± 1.11	258.69	283.75	25.05 ± 1.22
Tropopause												
Ht (km)	9.483	17.59	8.11 ± 0.55	8.50	17.57	9.07 ± 0.59	9.20	16.98	7.78 ± 0.47	9.22	16.89	7.67 ± 0.46
T (K)	188.96	218.69	29.73 ± 1.75	188.92	217.93	29.01 ± 1.80	192.80	221.18	28.38 ± 1.67	193.04	216.86	23.83 ± 1.60

latitudes in the equinoxes. von Zahn *et al.* (1996) reported that the mesopause is at 100 ± 3 km during winter for latitudes from 71°S to 23°N and at 86 ± 3 km during summer for latitudes from 24° to 54°N. Berger and von Zhan (1999) using a general circulation model of the middle atmosphere find mesopause structures in agreement with the one determined from observations.

Table 2 shows the descriptive statistics of the pauses obtained from figures 1 and 2. The minimum and maximum values and the range of the variation (standard deviation) in all the pauses are estimated independently for a given season. The maximum latitudinal variability in the altitude and temperature is observed in the mesopause followed by the tropopause and the minimum variability is observed in the stratopause in both NH winter and summer. This might be due to the tidal amplitudes which maximizes near the mesopause and in the case of tropopause, the direct influence of convection and gravity waves which are not completely removed in the averaging processes may provide such variability. In NH winter and summer, similar variability is noticed in both the mesopause and tropopause temperatures. In stratopause, we observe different variability in the altitude and temperatures between NH winter and summer with NH winter stratopause altitudes and temperatures slightly lower and higher, respectively.

During equinoxes, the tropopause shows the highest altitude variability followed by stratopause and the lowest variability is observed in the mesopause. Temperature changes are different in the spring and fall equinoxes. During the spring (fall) equinox, highest temperature variability is observed in the tropopause (stratopause) temperatures, but followed by the mesopause (tropopause) and minimum in the stratopause (mesopause) temperatures. Minimum variability in both the mesopause altitude and temperature was noticed in equinoxes when compared to NH winter and summer seasons. Whereas stratopause and tropopause altitudes show similar variability in all the seasons with respect to the latitude except in the fall and spring equinoxes for stratopause and tropopause, respectively.

3.2 *Latitudinal and longitudinal distribution of the pauses*

Figure 3 (figure 4) shows longitude–latitude sections of altitudes (temperatures) of all the pauses observed during NH winter, NH summer, spring, and fall equinox seasons averaged over the years 2002–2009 in 5°×5° bins. Though not clear from the figure, the longitudinal variation is more evident in NH winter (figure 3a) than in NH summer (figure 3d) in the tropopause. The off-equatorial maxima in both the hemispheres can be clearly seen at 0°–120°E (Africa to Indian Ocean) in NH summer and at 240°–360°E (America to the Atlantic) in NH winter. In the former, the tropopause is much higher around 20°–30°N. In the Pacific region, the tropopause altitudes increase from summer to winter hemispheres in both the seasons. A high tropopause altitude region between 60°–120°E and 20°–30°N in NH summer is noted. No significant longitudinal variations in the tropopause altitude are noticed during equinoxes though some features are visible around 60°S during fall equinox.

In NH winter (figure 4a), 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 (figure 4d) around 0°–120°E, it is known that the Asian monsoon circulation causes zonal asymmetry in the tropopause temperature and altitude (Ratnam *et al.* 2005). The tropical tropopause temperature in the NH winter is on average about 5 K lower than in the NH summer, and the altitude in the NH summer is about 0.5 km higher than in the NH winter. These results are consistent with previous studies (Schmidt *et al.* 2004, 2008; Añel *et al.* 2008; Son *et al.* 2011). Again, no significant longitudinal variations in the tropopause temperatures during equinoxes are noticed except near 60°S in fall equinox.

Longitudinal variation in the stratopause altitude is minimum in NH winter (figure 3b) in the tropical latitudes. However, large longitudinal variability in the stratopause altitude is noticed in mid-latitudes with lower altitudes over north Asian continent during NH winter. Similarly, low longitude variability in the stratopause altitude at polar latitudes with higher altitudes over North American Artic region can be noticed. Large longitudinal variability in the stratospheric temperature is noticed in North American Arctic region during NH winter (figure 4b) and Antarctic region during fall equinoxes. Relatively less longitudinal variability is noticed in the stratopause than in the tropopause and mesopause.

No significant longitudinal variability in the mesopause altitudes are noticed during NH winter at all the latitudes. Relatively low longitudinal variability with higher mesopause altitudes over Africa, Indian region, east of Indonesian region and South American region can be noticed over the equatorial latitudes. There exists large longitudinal variability in the mesopause altitudes during equinoxes at all the latitudes. Notable differences in the mesopause temperatures over the equator are found with lowest temperatures (∼150 K) around

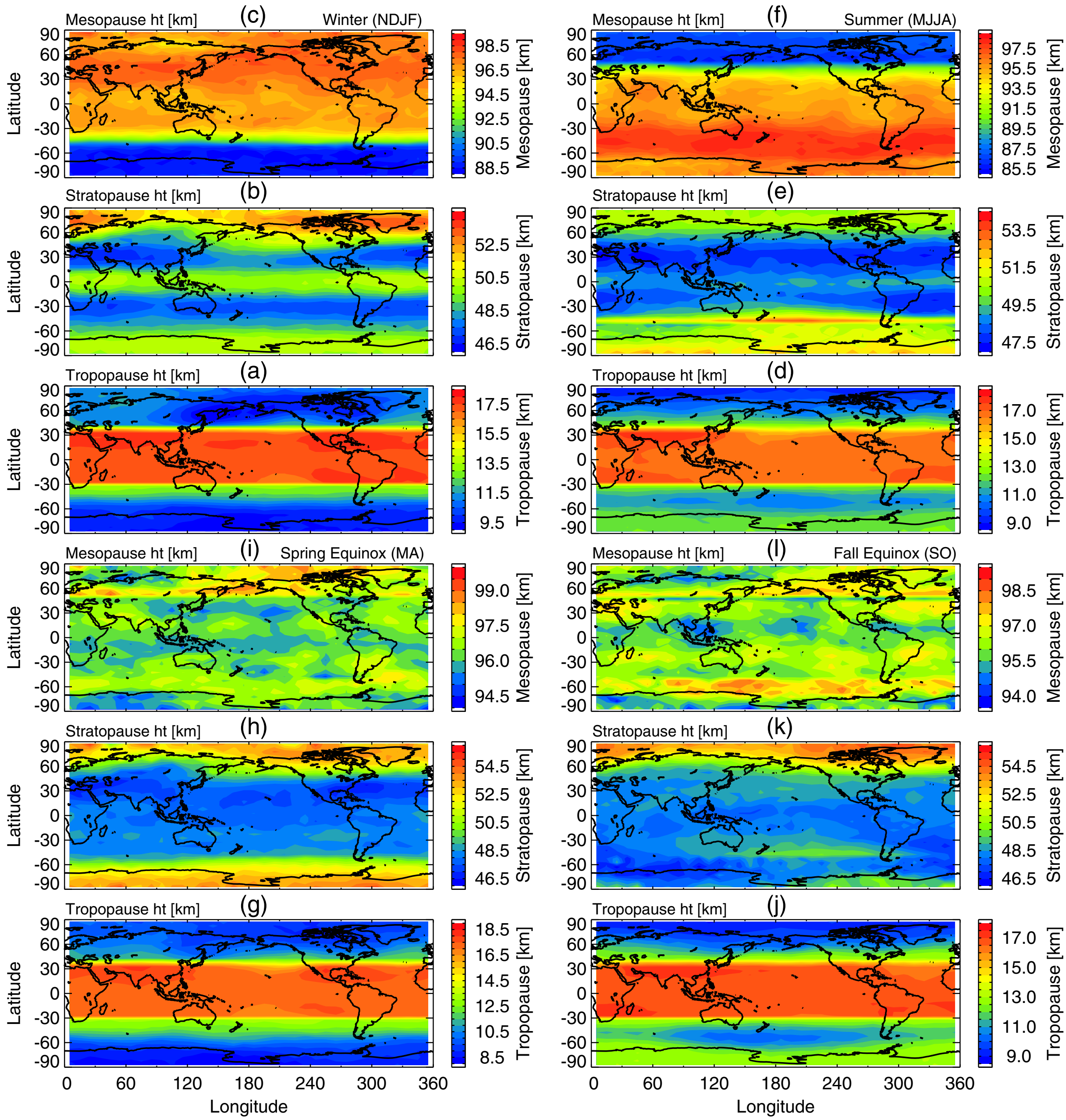

Figure 3. Global distribution of tropopause, stratopause and mesopause altitudes observed during NH winter (**a**–**c**), NH summer (**d**–**f**), spring equinox (**g**–**i**), and fall equinox (**j**–**l**) seasons using GPS RO (tropopause, 2002–2009) and SABER (stratopause and mesopause, 2002–2009) measurements.

Indian Ocean to Indonesian region and over South American region with pronounced variations during equinoxes. Large longitudinal variability in the northern polar mesopause temperatures can be noticed during equinoxes.

3.3 *Inter and intra-seasonal variations observed in the pauses*

In general, altitudes of all the pauses are zonally uniform to a leading order in the tropical latitudes (±30°), mid-latitudes (30°–60°N and S), and polar latitudes (60°–90°N and S). In order to study the inter and intra-seasonal variations, altitudes and temperatures of all the pauses are identified from the individual profiles and are averaged over a month within the tropical and mid-latitudes. Seasonal variation of these pauses over polar latitudes is not considered due to inadequate data. Figure 5 shows monthly mean variation of the tropopause, stratopause, and the mesopause altitudes and temperatures observed during 2002–2009 in the tropical latitudes (±30°) in both the hemispheres.

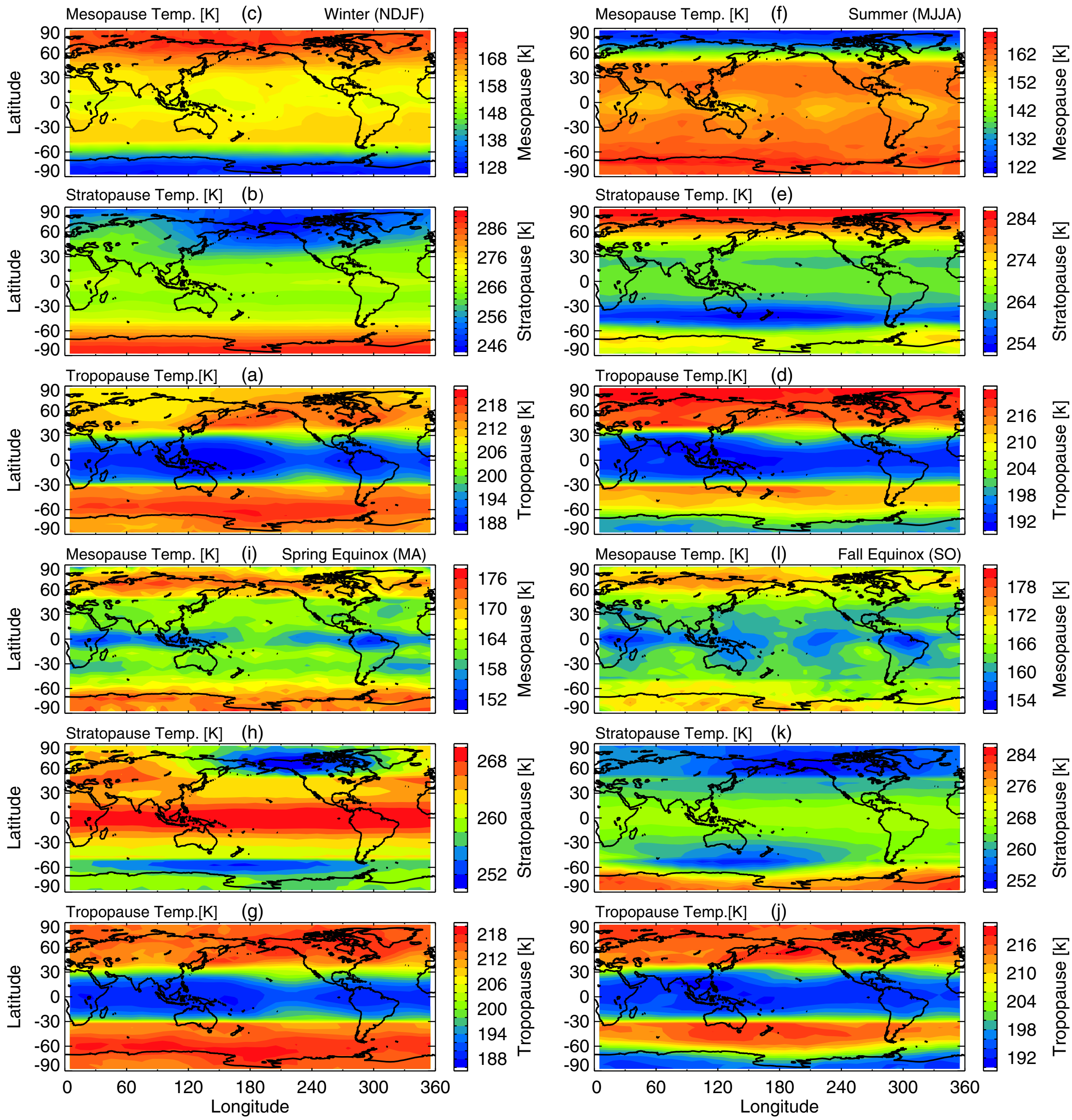

Figure 4. Same as figure 3 but for temperatures.

Figure 5 shows clear annual variation in the tropopause and mesopause altitudes, maximum in NH winter and minimum in NH summer seasons. However, there exists semi-annual variation in the tropical stratopause altitude with maximum during NH summer and winter seasons. Winter maximum is significantly higher than summer maximum. Higher variability in the tropopause and mesopause altitudes is noticed in NH than in SH within the tropical latitudes. Interestingly, on an average, the stratopause altitudes show higher variability in SH within the tropical latitudes. During NH winter, tropopause and mesopause altitudes are higher in SH than in NH. Large inter-annual variability is noticed in all the pauses altitudes though the magnitude of variability among the pauses differs.

In general, anti-correlation features (higher the altitude, lower the temperatures) are observed in the tropopause temperature to that of tropopause altitudes but the SH tropopause temperatures are significantly higher than NH tropopause temperatures during NH summer seasons. Similar temperatures are observed in both NH and SH during NH winter seasons. In contrast, stratopause and mesopause temperatures show similar magnitudes in both NH and SH. It is very interesting to see the decreasing trend in mesopause temperatures at the

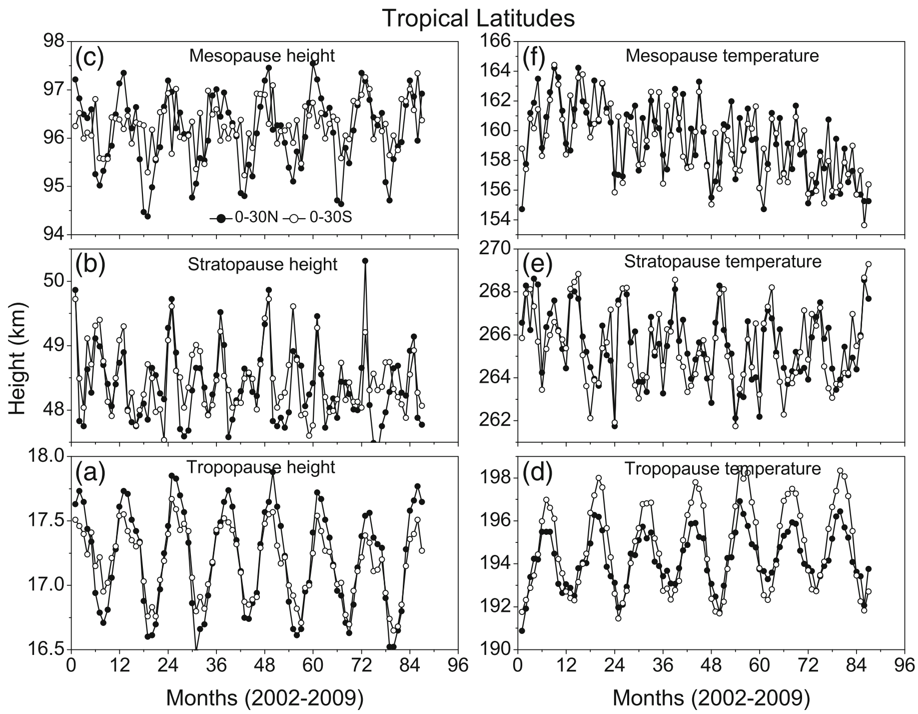

Figure 5. Monthly mean variation of **(a)** tropopause, **(b)** stratopause, and **(c)** mesopause altitudes (left panels) and temperatures (right panels) observed during 2002–2009 in the tropical latitudes (±30°).

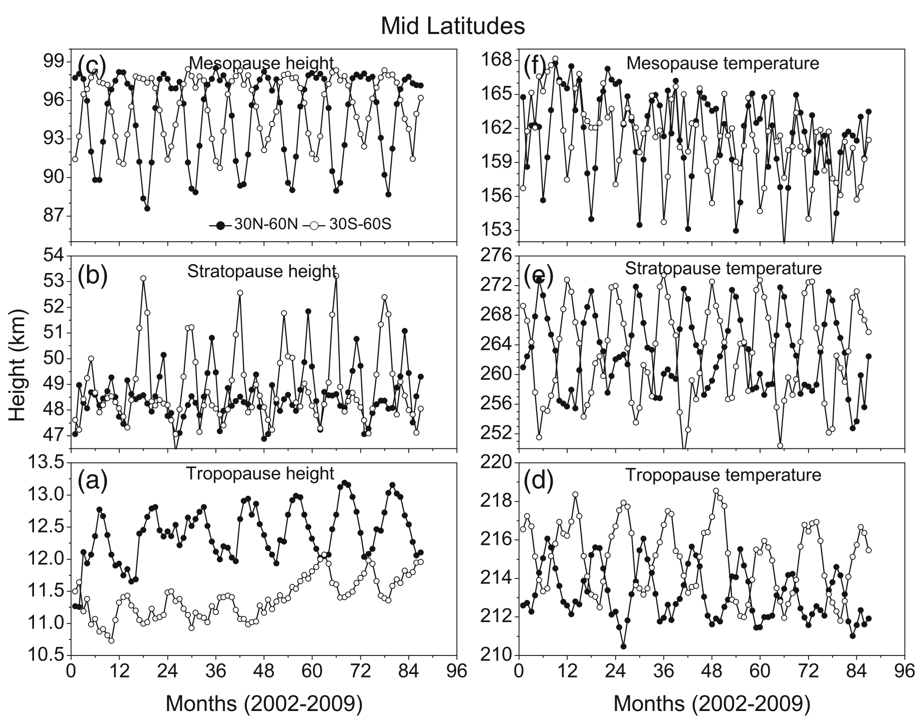

Figure 6. Same as figure 5 but for mid-latitudes.

rate of 0.72 K/year consistent with that reported by Ratnam *et al.* (2010). Readers are referred to She *et al.* (2009) and references therein for trends at other locations. Mesopause temperatures do not exhibit any systematic seasonal variation unlike the tropopause and the stratopause temperatures.

Monthly mean variation of tropopause, stratopause, and mesopause altitudes and temperature observed during 2002–2009 in the mid latitudes (30°–60°) in both the hemispheres is shown in figure 6. Annual oscillation in the tropopause and mesopause altitudes is again noticed with higher (lower) altitudes during NH summer (winter). The mid-latitude mesopause variations appear to be larger than in the tropics. There is also a clear positive (slightly negative) trend in mid-latitude (tropical) tropopause altitudes, which agree with previous studies (Schmidt *et al.* 2008). Annual oscillation is also noticed in the stratopause altitudes. Mirror image pattern in the tropopause and mesopause altitudes, i.e., higher (lower) altitudes in NH winter (summer) can be noticed between NH and SH mid-latitudes. NH mid-latitude tropopause shows more systematic pattern than SH mid-latitudes. Although maximum altitudes during NH winter (summer) are noticed in NH (SH) mid-latitudes, NH mid-latitudes show lower mesopause altitudes than SH mid-latitudes but the maximum altitude remains same in both the hemispheres. Interestingly, SH stratopause altitudes are higher than the NH mid-latitudes.

More systematic annual variation in tropopause and stratopause temperature can be noticed with mirror image pattern between NH and SH mid-latitudes. SH mid-latitude tropopause temperatures are warmer than NH during NH winter. However, SH mid-latitude stratopause temperatures are colder than NH mid-latitudes during NH summer. Slight decreasing trend in the mesopause temperatures can be noticed in both the hemispheres.

3.4 *Reference temperature profile*

In general, altitudes of all the pauses show similar features in the tropical latitudes, mid-latitudes, and polar latitudes. Thus, zonal mean temperature right from ground to 110 km is further averaged. Figure 7 shows the profiles of mean temperature in tropical, mid- and polar latitudes in both the hemispheres observed during NH summer (June in NH and December in SH) month averaged during 2002–2009 along with standard deviations. Note that above 85 km, standard deviations are not marked as we have used only one data namely SABER. Also note that maximum standard deviations are noticed in the lower troposphere in the NH than in SH and minimum standard deviations in SH high latitudes. Maximum standard deviations are also noticed in the high latitude mesosphere and minimum in the tropical altitudes. Although this analysis is repeated for other months, we report only for NH summer month to discuss the commonality and differences between the profiles of the temperature though it can be applied to other months as well. Sharp changes near the tropopause in the tropical latitudes, broad changes in the mid-latitudes and again sharp changes with temperature nearly constant above up to 25 km can be noticed in NH. Similar features are found in SH in both tropical and mid-latitudes but very sharp changes occur near the polar tropopause. Colder

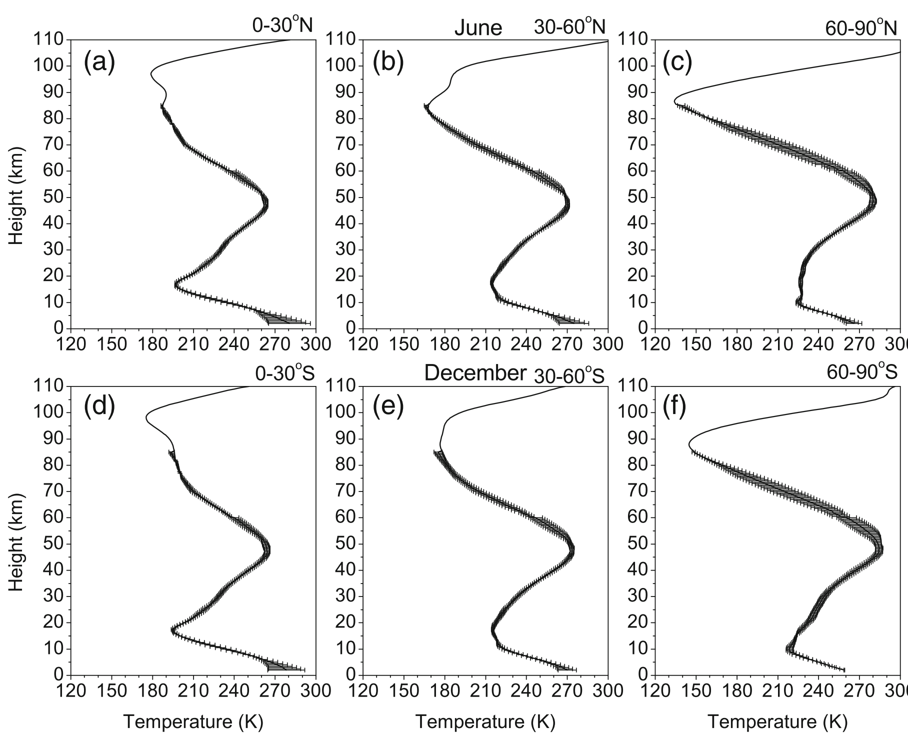

Figure 7. Profiles of temperature observed in **(a)** tropical latitudes (0°–30°N), **(b)** mid-latitudes (30°–60°N), and **(c)** polar latitudes (60°–90°N) during the month of June. **(d)–(f)** same as **(a)–(c)** but for southern hemisphere during the month of December. Horizontal bars show the standard deviation obtained while integrating various datasets.

temperatures near the tropopause in the SH was found within the tropical latitudes than NH. Similar variations in the stratopause behaviour can be noticed in both the hemispheres. Stratopause temperatures are hotter in polar latitudes than in mid-latitudes and minimum in tropical latitudes in both the hemispheres, however, stratopause is hotter in SH than in NH.

Sharp mesopause below 100 km (85 km) can be noticed in both the hemispheres in tropical (polar) latitudes, whereas it shows broad minimum in mid-latitudes. SH mesopause is broader than the NH mesopause in mid-latitudes. A significant difference in the temperatures near the mesopause can be noticed between NH and SH in both the tropical and mid-latitudes. This large variation in rapid temperature decrease makes the mesosphere unstable and causes large convective (vertical) currents. The main dynamical features in this region are the atmospheric tides which are driven by momentum propagating upwards from the lower atmosphere and extending into the lower thermosphere. There is indication of larger amplitude seasonal variations in the NH than in the SH, which could be related to the greater fraction of land-covered surface there.

Although some variability among different datasets exists, in general, other data sources fairly match well (figure not shown) with the GPS RO below the stratopause. Any differences are partly due to different resolution of the data available though the accuracy of the measurements remains same among different datasets which are clear from table 1. Differences observed in the tropopause altitudes and temperatures between GPS RO and other datasets, stratopause and mesopause altitudes and temperatures between SABER and other datasets during NH winter seasons at different latitudinal bands is provided in table 3. Values obtained during NH summer seasons are provided in brackets. As mentioned earlier, we take tropopause parameters from GPS RO and stratopause and mesopause parameters from SABER as a reference value. Thus, long-term original values of tropopause are also provided from GPS RO measurements and values of stratopause and mesopause altitudes and temperatures from SABER in table 3.

In general, less difference in the tropopause altitudes and temperature exists in the NH mid- and polar latitudes in the model datasets than other satellite measurements during NH winter. JRA-25 dataset show better comparisons than UKMO and ERA-Interim in the tropopause and stratopause. It is interesting to see negative bias in tropical tropopause temperatures in model outputs consistent with that reported by Randel *et al.* (2000). Stratopause altitudes and temperatures are moderately underestimated in other satellite and model datasets when compared to SABER at all the latitude bands. In general, CIRA-86 model profiles matches well below the stratopause with SABER measurements, however, large difference in altitude and temperature can be noticed above, particularly near the mesopause and above in all the latitudes, except in SH polar latitudes. Large difference in MLS temperatures and the altitudes can be noticed when compared to SABER and CIRA-86 data above the stratopause in all the latitudes.

4. Discussion

Here we find, in agreement with previous studies (Hoinka 1998; Son *et al.* 2011) a large asymmetry between tropopause altitudes in the NH and SH as a consequence of the greater fraction of land coverage in NH. Note that Hoinka (1998) and Son *et al.* (2011) have attributed the zonal asymmetries in NH winter with the storm tracks and stationary waves. In addition, we show that these asymmetries continue up to the mesopause. Besides the modification of these pauses by different wave sources, perhaps the only parameter that could be related to all these pauses together is the variability in carbon dioxide (CO_2) as it is well distributed in the entire middle atmosphere. Several studies (Ratnam *et al.* 2006 and references therein) were carried out on the modulation of tropopause altitudes and temperatures with wave effects generated due to variety of sources, and the reasons for such variability in the stratopause and mesopause are meager.

It is difficult to resolve the variability in the tropopause and stratopause with that of CO_2, however, cooling near the mesopause could be due to the increase in atmospheric CO_2. Solar cycle could also affect the mesopause temperatures (and altitudes) but the dataset available presently is not adequate to discuss this effect. Since the observations considered are during the declining phase of solar cycle, it is quite likely that the observed effect is partly due to solar flux variability as also mentioned in Ratnam *et al.* (2010).

5. Summary and conclusions

In the present study, we have presented the behaviour of all the pauses (tropopause, stratopause, and mesopause) observed near simultaneously using long-term data (2002–2009) from GPS RO and SABER satellite measurements. The main findings are summarized below:

- Mesopause shows the maximum variability in altitude and temperature followed by the

Table 3. *Differences observed in the tropopause altitudes and temperatures between GPS RO and other datasets, stratopause and mesopause altitudes and temperatures between SABER and other datasets during NH winter (summer) seasons at different latitudinal bands. Long-term original values of tropopause are obtained from GPS RO measurements and values of the stratopause and the mesopause altitudes and temperatures from SABER.*

	Tropopause							
	GPS RO	AIRS_AQUA	HIRDLS	AURA_MLS	CIRA-86	ERA-Interim	JRA-25	UKMO
0°–30°N								
Ht	17.5 (16)	1 (1)	0.5 (0)	0 (−0.5)	1.4 (0.9)	1 (1)	1 (5.5)	1 (1)
T	194.9 (195.93)	−0.12 (1)	−0.93 (−0.85)	2.25 (1.33)	−3.46 (−2.91)	−0.48 (0.39)	−0.88 (−0.33)	−0.12 (−0.12)
30°–60°N								
Ht	18.5 (16.5)	0 (1)	0.5 (0)	−0.5 (0)	0.9 (1.4)	0 (1)	0 (1)	0 (1)
T	212.95 (214.16)	0.53 (0.73)	0.4 (0.43)	2.08 (2.05)	−0.58 (−1.08)	0.7 (0.82)	0.46 (0.4)	0.98 (1)
60°–90°N								
Ht	13 (10.5)	2.5 (−0.5)	0 (0)	2 (0.5)	−0.1 (−1.4)	0 (−0.5)	0 (0.5)	0 (−1.5)
T	213.54 (225.83)	1.48 (−1.46)	0.2 (−2.54)	1.36 (2.07)	−1.7 (−2.87)	0.34 (−1.17)	0.37 (−1.04)	−0.38 (−2.71)
0°–30°S								
Ht	17.5 (16.5)	1 (0.5)	0.5 (0)	0 (−0.5)	1.4 (0.9)	1 (1)	1 (0.5)	1 (0.5)
T	194.73 (197.54)	0.28 (0.46)	−1.03 (−0.58)	1.86 (1.46)	−3.54 (−2.8)	−0.46 (0.47)	−0.73 (−0.05)	0.03 (0.24)
30°–60°S								
Ht	17 (16)	0.5 (3)	0 (3)	−0.5 (2.5)	0.9 (3)	0.5 (4.5)	0.5 (2.5)	0.5 (3.5)
T	215.55 (212.71)	1.39 (−0.85)	−0.7 (−1.04)	2.04 (−3.16)	−1.14 (−4.11)	0.84 (−2.51)	0.52 (−1.26)	1.42 (−1.62)
60°–90°S								
Ht	9.5 (10.5)	−1 (−0.5)	−0.5 (0)	0 (−0.5)	−0.3 (−1.4)	−1 (−1.5)	−0.5 (0.5)	−2 (−1)
T	218.44 (208.15)	2.56 (0.93)	−4.02 (−4.86)	2.21 (1.39)	−3.2 (−1.1)	1.77 (1.92)	−0.2 (−2.61)	−1.28 (0.39)

Table 3. *(Continued.)*

Stratopause

	SABER	GPSRO	HIRDLS	AURA_MLS	CIRA-86	ERA-Interim	JRA-25	UKMO
0°–30°N								
Ht	47.5 (47)	−2 (−0.5)	0 (−0.5)	−1 (−1.5)	0.3 (−0.2)	–	−0.5 (−1)	−0.5 (−0.5)
T	259.5 (261.28)	−2.95 (−1.1)	−2.47 (−2.85)	−4.6 (−4.08)	−6.5 (−5.02)	–	−6.53 (−7.5)	−3.53 (−1.95)
30°–60°N								
Ht	47.5 (47.5)	−2 (−3.5)	−1 (0)	−3.5 (−1)	−1.7 (0.3)	–	−0.5 (−0.5)	−3.5 (0)
T	252.88 (269.05)	−0.39 (0.19)	−0.87 (−2.34)	−2.35 (−2.79)	−3.59 (−4.69)	–	−2.21 (−5.78)	−4.14 (0.01)
60°–90°N								
Ht	– (51)	– (−1)	– (2)	– (2.5)	– (3.8)	–	– (3)	– (3)
T	– (281.04)	– (3.64)	– (−0.26)	– (−1.93)	– (−1.48)	–	– (−7.94)	– (1.08)
0°–30°S								
Ht	47 (47.5)	−2 (−1)	−0.5 (−0.5)	−1.5 (−1)	−0.2 (−1.7)	–	−1 (−0.5)	−1 (−0.5)
T	261.11 (259.76)	−3.19 (−0.52)	−3.19 (−3.07)	−5.82 (−5)	−7.42 (−4.6)	–	−8.62 (−7.12)	−4.12 (−1.8)
30°–60°S								
Ht	47.5 (51)	−3.5 (0)	0 (1.5)	−1 (0)	2.3 (−2.1)	–	−0.5 (–)	−0.5 (−1)
T	271.12 (248.81)	−2.3 (−5)	−3.56 (−2.19)	−4.1 (−2.82)	−6.54 (−6.65)	–	−6.71 (–)	−1.86 (−5.99)
60°–90°S								
Ht	51 (–)	−1 (–)	2.5 (–)	2.5 (–)	5.8 (–)	–	3 (–)	3 (–)
T	284.14 (–)	−2.87 (–)	3.5 (–)	−3.63 (–)	−1.54 (–)	–	−8.49 (–)	−1.5 (–)

Mesopause

	SABER	AIRS_AQUA	HIRDLS	AURA_MLS	CIRA-86	ERA-Interim	JRA-25	UKMO
0°–30°N								
Ht	99 (97)	–	–	−3 (0)	2.9 (3.7)	–	–	–
T	177.54 (178.88)	–	–	1.93 (7.75)	−9.43 (−5.03)	–	–	–
30°–60°N								
Ht	100 (84)	–	–	3 (−7.5)	2.5 (−8)	–	–	–
T	181.94 (167.72)	–	–	5.93 (7.97)	−9.43 (3.66)	–	–	–
60°–90°N								
Ht	– (86.5)	–	–	– (−10)	– (−2.7)	–	–	–
T	– (134.07)	–	–	– (5.39)	– (−6.91)	–	–	–
0°–30°S								
Ht	98 (98.5)	–	–	2 (1.5)	4.7 (2.4)	–	–	–
T	175.3 (180.84)	–	–	−0.83 (8.2)	−8.61 (−6.13)	–	–	–
30°–60°S								
Ht	88 (99.5)	–	–	−8.5 (2.5)	−2.6 (2)	–	–	–
T	176.57 (178.01)	–	–	15.66 (−5.75)	12.27 (−13.48)	–	–	–
60°–90°S								
Ht	88 (–)	–	–	−8.5 (–)	0.3 (–)	–	–	–
T	144.81 (–)	–	–	18.22(–)	3.05(–)	–	–	–

tropopause and then by the stratopause in both NH winter and NH summer. Mesopause altitude shows the overall highest latitudinal variability.

- In the SH, tropopause and mesopause altitudes show a simultaneous gradual decrease with decrease in latitude while corresponding temperatures show abrupt increase. At similar latitudes stratopause altitude (temperature) showed local minimum (maximum).
- We find larger longitudinal variability in the tropopause altitudes and temperatures than in the stratopause and mesopause ones. The altitude and temperature of tropopause show maximum longitudinal variability during the NH summer and winter, respectively.
- All the pauses display large seasonal variations in the NH than in the SH.
- Within the tropical latitudes, the tropopause and mesopause altitudes show higher variability in the NH than in the SH. For the same latitude range stratopause altitudes show higher variability in SH.
- At mid-latitudes the maximum altitude variability of the pauses in the NH and the SH is observed in winter and summer, respectively. The maximum mesopause altitude is same in both hemispheres while the minimum mesopause altitude is observed in the NH.
- All pauses show large inter-annual variability in altitudes and temperatures.
- In general, various datasets (other satellites and model outputs) show similar features in all the pauses, however, large differences in their altitudes and temperatures are noticed when compared to GPS RO and SABER.

This study compares spatial and seasonal variability of all the pauses and quantifies the differences. Future work will investigate the cause of the observed variability.

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References

Añel J A, Antuña J C, de la Torre L, Castanheira J M and Gimeno L 2008 Climatological features of global multiple tropopause events; *J. Geophys. Res.* **113** D00B08, doi: 10.1029/2007JD009697.

Anthes R A *et al.* 2008 The COSMIC/FORMOSAT-3 mission: Early results; *Bull. Am. Meteor. Soc.* **89** 1–21.

Aumann H H *et al.* 2003 AIRS/AMSU/HSB on the Aqua Mission: Design, science objectives, data products, and processing systems; *IEEE Trans. Geosci. Rem. Sens.* **41** 2.

Beagley S R, de Grandpré J, Koshyk J N, McFarlane N A and Shepherd T G 1997 Radiative-dynamical climatology of the first-generation Canadian middle atmosphere model; *Atmos. Ocean* **35** 293–331.

Berger U and von Zhan U 1999 The two-level structure of the mesopause: A model study; *J. Geophys. Res.* **104** 22,083–22,093.

Birner T 2010 Recent widening of the tropical belt from global tropopause statistics: Sensitivities; *J. Geophys. Res.* **115** D23109, doi: 10.1029/2010JD014664.

Dee D P and Uppala S 2009 Variational bias correction of satellite radiance data in the ERA-Interim reanalysis; *Quart. J. Roy. Meteorol. Soc.* **135** 1830–1841.

García-Comas M *et al.* 2008 Errors in Sounding of the Atmosphere using Broad band Emission Radiometry (SABER) kinetic temperature caused by non-local thermodynamic-equilibrium model parameters; *J. Geophys. Res.* **113** D24106, doi: 10.1029/2008JD010105.

Gettelman A, Hoor P, Pan L L, Randel W J, Hegglin M I and Birner T 2011 The extra tropical upper troposphere and lower stratosphere; *Rev. Geophys.* **49** RG3003, doi: 10.1029/2011RG000355.

Gille J *et al.* 2008 High Resolution Dynamics Limb Sounder: Experiment overview, recovery, and validation of initial temperature data; *J. Geophys. Res.* **113** D16S43, doi: 10.1029/2007JD008824.

Hitchman M H and Leovy C B 1986 Evolution of the zonal mean state in the equatorial middle atmosphere during October 1978–May 1979; *J. Atmos. Sci.* **43** 3159–3176.

Hitchman M H, Gille J C, Rodgers C D and Brasseur G 1989 The separated polar winter stratopause: A gravity wave driven climatological feature; *J. Atmos. Sci.* **46** 410–422.

Hoinka K P 1998 Statistics of the global tropopause pressure; *Mon. Weather. Rev.* **126** 3303–3325.

Jiang J H *et al.* 2004 Comparison of GPS/SAC-C and MIPAS/ENVISAT temperature profiles and its possible implementation for EOS MLS observations, in CHAMP mission results for gravity and magnetic field mapping, and GPS atmospheric sounding; (Berlin/Heidelberg/New York: Springer), pp. 573–578.

Kiladis G N, Straub K H, Reid G C and Gage K S 2001 Aspects of interannual and intraseasonal variability of the tropopause and lower stratosphere; *Quart. J. Roy. Meteorol. Soc.* **127** 1961–1983.

Kishore Kumar G, Venkat Ratnam M, Patra A K, Vijaya Bhaskara Rao S and Russell J 2008 Mean thermal structure of the low-latitude middle atmosphere studied using Gadanki Rayleigh lidar, Rocket, and SABER/TIMED observations; *J. Geophys. Res.* **113** D23106, doi: 10.1029/2008JD010511.

Kursinski E R, Hajj G A, Schofield J T, Linfield R P and Hardy K R 1997 Observing the Earth's atmosphere with radio occultation measurements using the Global Positioning System; *J. Geophys. Res.* **102** 23,429–23,465.

Labitzke K, Barnett J J and Edwards B (eds) 1985 Middle Atmosphere Program; *MAP Handbook*, **16**. University of Illinois, Urbana.

Lorenc A C, Ballard S P, Bell R S, Ingleby N B, Andrews P L F, Barker D M, Bray J R, Clayton A M, Dalby T, Li D, Payne T J and Saunders F W 2000 The Met. Office global three-dimensional variational data assimilation scheme; *Quart. J. Roy. Meteorol. Soc.* **126(570)** 2991–3012.

Manney G L, Schwartz M J, Kruger K, Santee M L, Pawson S, Lee J N, Daffer W L, Fuller R A and Livesey N J 2009 Aura Microwave Limb Sounder observations of dynamics and transport during the record-breaking 2009 Arctic stratospheric major warming; *Geophys. Res. Lett.* **36** L12815, doi: 10.1029/2009GL038585.

Mertens C J, Mlynczak M G, Lopez-Puertas M, Wintersteiner P P, Picard R H, Winick J R, Gordley L L and Russell III J M 2001 Retrieval of mesospheric and lower thermospheric kinetic temperature from measurements of CO_2 15-μm Earth limb emission under non-LTE conditions; *Geophys. Res. Lett.* **28** 1391–1394.

Onogi K *et al.* 2007 The JRA-25 Reanalysis; *J. Meteor. Soc. Japan* **85** 369–432.

Randel W J, Wu F and Gaffen D 2000 Interannual variability of the tropical tropopause derived from radiosonde and NCEP reanalysis; *J. Geophys. Res.* **105** 15,509–15,523.

Ratnam M V, Shen C M, Chen W N and Nee J B 2004 Study on oxygen atmospheric band dayglow: Global and seasonal variations deduced from high-resolution Doppler imager observations; *J. Atmos. Sol. Terr. Phys.* **66** 209–218.

Ratnam M V, Tsuda T, Shiotani M and Fujiwara M 2005 New characteristics of the tropical tropopause revealed by CHAMP/GPS measurements; *SOLA* **1** 185–188, doi: 10.2151/sola.2005-048.

Ratnam M V, Tsuda T, Mori S and Kozu T 2006 Modulation of tropopause temperature structure revealed by simultaneous radiosonde and CHAMP GPS measurements; *J. Meteor. Soc. Japan* **84** 989–1003.

Ratnam M V, Patra A K and Krishna Murthy B V 2010 Tropical mesopause: Is it always close to 100 km?; *J. Geophys. Res.* **115** D06106, doi: 10.1029/2009JD012531.

Santer B D, Sausen R, Wigley T M L, Boyle J S, Achuta R K, Doutriaux C, Hansen J E, Geehl G A, Roeckner E, Ruedy R, Schmidt G and Taylor K E 2003 Behavior of tropopause altitude and atmospheric temperature in models, reanalysis, and observations: Decadal changes; *J. Geophys. Res.* **108(D1)** 4002, doi: 10.1029/2002JD002258.

Schmidt T, Wickert J, Beyerle G and Reigber C 2004 Tropical tropopause parameters derived from GPS radio occultation measurements with CHAMP; *J. Geophys. Res.* **109** D13105, doi: 10.1029/2004JD004566.

Schmidt T, Wickert J, Beyerle G and Heise S 2008 Global tropopause height trends estimated from GPS radio occultation data; *Geophys. Res. Lett.* **35** L11806, doi: 10.1029/2008GL034012.

She C Y, David A Krueger, Rashid Akmaev, Hauke Schmidt, Elsayed Talaat and Sam Yee 2009 Long-term variability in mesopause region temperatures over Fort Collins, Colorado (41°N, 105°W) based on lidar observations from1990 through 2007; *J. Atmos. Sol. Terr. Phys.* **71** 1558–1564.

Sivakumar V, Bencherif H, Hauchecorne A, Keckhut P, Rao D N, Sharma S, Chandra H, Jayaraman A and Rao P B 2006 Rayleigh lidar observations of double stratopause structure over three different northern hemisphere stations; *Atmos. Chem. Phys. Discuss.* **6** 6933–6956, doi: 10.5194/acpd-6-6933-2006.

Son S W, Tandon N F and Polvani L M 2011 The fine-scale structure of the global tropopause derived from COSMIC GPS radio occultation measurement; *J. Geophys. Res.* **116** D20113, doi: 10.1029/2011JD016030.

Tomikawa Y, Sato K, Watanabe S, Kawatani Y, Miyazaki K and Takahashi M 2008 Wintertime temperature maximum at the subtropical stratopause in a T213L256 GCM; *J. Geophys. Res.* **113** D17117, doi: 10.1029/2008JD009786.

von Zahn U, Hoffner J, Eska V and Alpers M 1996 The mesopause altitude: Only two distinctive levels worldwide? *Geophys. Res. Lett.* **23** 3231–3234.

Waters J W *et al.* 2006 The Earth Observing System Microwave Limb Sounder (EOS MLS) on the Aura Satellite; *IEEE Trans. Geosci. Rem. Sens.* **44** 5.

Wickert J, Reigber C, Beyerle G, König R, Marquardt C, Schmidt T, Grunwaldt L, Galas R, Meehan T K, Melbourne W G and Hocke K 2001 Atmosphere sounding by GPS radio occultation: First results from CHAMP; *Geophys. Res. Lett.* **28** 3263–3266.

World Meteorological Organization (WMO), Definition of the tropopause 1957; *WMO Bull. 6*, Geneva, Switzerland.

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