Global Trends of Tropopause Observed from COSMIC Radio Occultation Technique during 2007-2012

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ABSTRACT- Global trends of tropical tropopause are examined using unprecedented resolution data sets of atmospheric refractivity, temperature, pressure and water vapor in the lower atmosphere. This paper presents seasonal and monthly trends of global cold point tropopause using temperature profiles retrieved from COSMIC GPS RO technique during 2007-2012. The observed trends with respect to temperature and pressure on individual locations and over the globe are validated using COSMIC retrieved, nearby radiosonde measurements and data sets provided by National Centers for Environmental Prediction re-analysis (NCEP) which showed a good agreement between them with few exceptions. It has been observed that both seasonal and monthly trends of cold point tropopause are similar to that of earlier observations made using the same technique. A systematic difference is observed between June and December solstice seasons, although both equinox seasons (March and September) are showing almost equal trends. No specific relation is found between tropical tropopause and outgoing long-wave radiation (OLR) trends during different seasons, confirming that the tropical tropopause is not solely controlled by localized deep convection and it is expected that convectively generated waves might play a significant role. The highest values are noticed during the northern winter months (December solstice) in the deep tropics during different months of 2007-2012 study period, although tropical tropopause heights show nearly constant trends.

KEYWORDS: COSMIC RO technique, radiosonde measurements, temperature, pressure and cold-point tropopause

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1. INTRODUCTION

The thermodynamics of tropical cold- point tropopause (CPT), a thermal boundary that often uses to distinguish the stratosphere and troposphere regions of the Earth's atmosphere, have been recognized to play a significant role in stratosphere-troposphere coupling and exchange [16]. Mainly, it is known that temperatures at the CPT control, to a great extent, transport of water vapor that tends to enter from the troposphere to the stratosphere. As the air that enters the stratosphere via the tropical tropopause undergoes a freeze-drying process near the CPT [9], the amount of water vapor transported into the stratosphere is highly dependent on the thermal characteristics of the CPT [16], [21].

Further, it is also known that small changes in water vapor in the stratosphere can drive significant changes in the climate below by modifying the global radiation budget [12], [16]. Recently, it has also been shown that long-term change of the global tropopause is a useful 'fingerprint' of global climate change [27}, [32] based on anthropogenic warming and stratospheric ozone depletion. It has been noticed that due to anthropogenic warming and stratospheric ozone depletion, global tropopause pressure (height) has been increasing (decreasing) during the last four decades. These important implications show the utmost need to study accurately the structure and long-term behavior of the tropopause.

Not only due to their availability of records for the last seven decades at many tropical locations and also due to their capability in offering in-situ, high-resolution temporal and spatial sampling of the vertical temperature and moisture structures, the physical properties of CPT have been reported in the literature by analyzing radiosonde measured temperatures [25], [29], [30], [38]. Certain important aspects have been revealed by radiosonde measurements, although a clear picture on large-scale structure such as the latitude-longitude structure of the global tropopause has not been possible. For instance, it was confirmed unambiguously that tropopause height reaches its highest altitude in the tropics, drops sharply across the subtropical jest, and settles to lower altitudes in the extratropics. Although reanalysis datasets including the European Centre for Medium-Range Weather Forecasts (ECMWF) 40 Year- Re-analysis (ERA-40) and the National Centers for Environmental Protection- National Center for Atmospheric Research (NCEP-NCAR) Reanalysis (NNR) are available to the community as alternatives, questions have been raised about their quality and coarse vertical resolutions [5], [17], [28].

Global Positioning System (GPS) radio occultation (RO) technique, on the other hand, assumes great significance in those scenarios as it can provide global coverage, high accuracy, high vertical resolution (less than 1 km), long-term stability, self-calibration and capability to operate in all-weather conditions [18], [36]. With GPS RO technique, it is possible to collect the global high-resolution data sets of atmospheric refractivity, temperature, pressure, and water vapor profiles in the lower atmosphere and electron density profiles of both E and F-regions of the upper atmosphere (ionosphere). The earth's atmosphere has been monitored with earlier RO techniques including mono-satellite GPS/MET [20], CHAllenging Mini satellite Payload (CHAMP; Wickert et al., 2001) and Satellite de Aplicaciones Cientificas- C [13], which primarily suffered from sparse sampling (both temporal and spatial). Nevertheless, the launch of six COSMIC (Constellation Observing System for Meteorology, Ionosphere and Climate) satellites provide an order of magnitude increase in the number of GPS-RO profiles available [2]. It has been estimated that COSMIC satellites

provide approximately ~12 times higher database than the earlier RO missions and, on average, ~1500- 2000 profiles will be available during a day around the globe [2],[6]. It is, therefore, expected that the COSMIC constellation will provide much more detailed analysis of both lower and upper atmosphere. It is true that COSMIC GPS RO technique has already provided a few significant research results in the lower atmosphere and ionospheric altitudes [1], [6], [7], [8], [10], [11], [24], [35].
The organization of this article is as follows. A brief introduction of the COSMIC GPS RO technique is presented in section 2. Sections 3.1 and 3.2 present typical comparisons between temperature and pressure profiles on 1 March 2007 and during March equinox (March-May) season in 2007. Section 3.3 presents tropopause seasonal trends from 2007 to 2012 & monthly variations of CPT between 2007 and 2012. Finally, conclusions are presented in section 4.

2. SIGNIFICANCE OF GPS RO TECHNIQUE

GPS RO methods differ from most other satellite remote sensing methods in that these are coming under active remote sensing techniques and use measurements of phase, rather than intensity. As the GPS signals are regulated by atomic clocks, the GPS occultation measurements do not need additional calibration. These features, thus, make the GPS RO technique a new and precise sounding technique for the earth's atmosphere and it has the potential to improve weather analyses, to monitor climate change, and to provide ionospheric data at higher resolution and better accuracy. The earlier RO missions (GPS/MET, CHAMP, SAC-C) had refined the systems and techniques of GPS sounding that led to set the stage for COSMIC, the first operational GPS occultation constellation. COSMIC satellites (six in number) were launched in low-earth orbits (800 km) jointly by Taiwan's National Space Organization (NSPO) and United States UCAR in the month of April 2006.
Most importantly, the earlier GPS RO techniques including GPS/MET and CHAMP have often suffered with the inability of recording and retrieving rising occults and inability to penetrate the lowest 2 km in the tropical troposphere, because of the usage of a traditional phase-locked loop (PLL) in their LEO satellite receivers. The close-loop (CL) tracking approach of PLL in LEO receiver utterly fails to lock on signals associated with high dynamics that often present in atmospheric boundary layer [4], as the PLL adjusts the frequency of the reference signal on the basis of previous measurements, instead of taking care of the original signal. It is very true that the CL approach works well when there is sufficient signal-to-noise (SNR) and the signal dynamics are not too high, which is often not the case, particularly, in and around the atmospheric boundary layer. However, in order to study a few important atmospheric convective parameters, which are very much sensitive to temperatures and moisture profiles near the lower troposphere, the atmospheric profiles below 5 km would be necessary. Since the COSMIC satellites have been implemented with an open-loop (OL) tracking approach, wherein the reference signal is 'guessed' based on knowledge of the orbits, receiver clock drift, and estimate of the atmospheric Doppler shift and delay, more than 90% of COSMIC soundings penetrate below 1 km [4].

3. GLOBAL DATA BASE

Before presenting the important observational results of this study, we have shown the number of occultations COSMIC constellation could provide globally. Figure 1 shows the number of citations (1465) made by COSMIC satellites (blue circles) and locations of radiosonde instruments (667) globally on 1 March 2007. One can understand from Figure 1 that the number of occultations is extremely high for the latitude sector 80^0S- 80^0N, which is due to the high inclination of COSMIC micro-satellites (78^0), while the coverage in the equatorial region is relatively lesser than above latitudinal range. Another important observation is that near Polar regions (80^0-90^0) are marked with very low coverage.

3.1 Comparisons Of Location Specific Trends

Figure 2 left (right) panel depicts temperature (pressure) profile measured using nearby radiosonde, RO technique and provided by NCEP reanalysis data, respectively. In general, comparisons of temperature and pressure profiles among these independent observations reveal a good correspondence [1], [6], however with few following exceptions. For example, left (right) panel in Figure 1 shows temperature (pressure) profiles measured by COSMIC micro-satellite number 06, co-located radiosonde and NCEP reanalysis data at geographic latitude 0.07^0 S, geographic longitude 180.0^0 E on 1 March 2007 between 0 and 30 km. Here, geographic latitude and longitude represents a COSMIC satellite occultation location, whereas radiosonde measurements were taken 141 km and 01:45 hours away from the COSMIC satellite location. It is obvious that there is a slight difference in temperatures measured by these three independent observations from 0 to ~8 km altitude range, which is due to interference from water vapor existence at those altitudes. In addition, few differences in magnitudes of temperature are found below, at and near CPT, specifically between radiosonde and COSMIC retrieved profiles, an observational evidence that having similarities with earlier studies [17], [33], [37]. For example, Kishore et al.[17] performed a validation study using the operational stratospheric analyses, including NCEP, the Japanese 25- year Reanalysis (JRA-25) and the United Kingdom Met Office (UKMO) data sets. Good agreement was found between the COSMIC and the various reanalysis outputs, with mean global differences and differences in the height range from 8 to 30 km being less than 1 K. Largest deviations were observed spatially over polar latitudes and altitude-wise at the tropical tropopause with differences being 2–4 K. Collocated global atmospheric temperature profiles from radiosondes and from COSMIC GPS RO satellites have been compared from April 2008 to October 2009 by [33]. It was found by Sun et al. [33], that in troposphere the temperature standard deviations errors were 0.35 K per 3 h and 0.42 K per 100 km. Comparative studies made by [37] between GPS RO retrieved temperature profiles from both CHAMP and COSMIC satellites with radiosonde data from 38 Australian radiosonde stations have shown a very good agreement between the two data sets. Specifically, [37] have found the mean temperature difference between radiosonde and CHAMP to be 0.39^0 C, while it was 0.37^0 C between radiosonde and COSMIC satellites.
On the other hand, a cent percent consistency in magnitudes of pressure is found. It is, therefore, clear that temperature and pressure profiles show nearly good agreement between these three measurements, thereby providing confidence in using COSMIC RO retrieved temperatures in the studies of atmospheric dynamics and tropopause long-term trends.

3.2 Comparison Of Seasonal Trends

In order to verify the global trends of both temperature and pressure retrieved by COSMIC satellites, we present them during March equinox season of 2007. Figure 3 left (right) panel shows temperature (pressure) profiles, averaged between 5^0 S and 5^0 N latitudes, from 5 to 30 km range during March-May 2007. It is clear that temperature trends seem to have associated with decreasing tendencies with the progress of height starting from 5 km to ~17.5 km (tropopause), so-called temperature lapse rate, and are associated with increasing trends with the progress of time from ~17.5 km to 30 km. It is also interesting to note that the tropical tropopause is located at ~ 100 hPa pressure level as can be seen from the right panel of Figure 3. On the other hand, magnitudes associated with pressure, shown in the right panel of Figure 3, are decreasing with the progress of altitude monotonically starting from 5 km to 30 km.

It is well accepted that planetary wave structures such as Kelvin waves in temperature trends are concentrated near to equatorial tropopause region [22], [25], [26] and can influence tropopause structure significantly [25], [26], [34]. With a view to verify such wave characteristics, we have made an attempt to plot temperature trends near equatorial tropopause region (~between 5^0S and 5^0N) in the following lines. Figures 4a-4c show global temperature trends in the equatorial region at 15, 17 and 19 km altitude, respectively, during March- May 2007. It may be worth mentioning here that though a systematic procedure needs to be implemented to delineate Kelvin wave features from temperature trends such as one that proposed in our recent study [1], it is also possible to notice Kelvin waves by verifying longitude vs. day of year temperature plots, based on the fact that their inherent features including eastward propagation and global-scale zonal wavenumbers can easily be observed from those plots. It is obvious from Figure 4b that the eastward propagating waves are pretty evident at 17 km range, although such characteristics, with lesser magnitudes, can also be seen at 15 and 19 km altitude range (see Figures 4a and 4c). In order to show them more clearly, we have marked eastward propagations with inclined snuff color lines in Figure 4b. By doing so, it is found that Kelvin waves are associated with zonal wavenumber-2 with wave periodicities between around 12 and 18 days (so called slow Kelvin waves). We have made the same analysis for the remaining seasons as to know how Kelvin waves influenced CPT over this six year period (2007-2012) and some of the crucial results are discussed in the following sections.

3.3 Seasonal Specific Tropopause Trends

In order to verify the spatial structures of temperatures during different seasons, tropopause data during every three month period are put together as ensembles including during the September equinox (SON- September, October and November), December solstice (DJF-December, January and February), March equinox (MAM- March, April and May) and June solstice (JJA- June, July and August) seasons of different years (2007-2012).

Figures 5 (a-d) and 10 (a-d) show global tropopause trends, or spatial structures, during MAM, JJA, SON and DJF seasons in the span of the six year period (2007 -2012). In general, as expected, tropical locations are associated with a minimum of around -80^0 C (195 K) values during different seasons. Further, though both equinox seasons (Figures (a) and (c)) are showing equal trends, a systematic difference is noticed during June and December solstice seasons (Figures (b) and (d)). For example, northern polar regions during the JJA season (northern hemisphere summer) are associated with higher temperatures (~-50^0 C) compared to southern polar regions (~-80^0 C). Contrary to the JJA season trends, reverse temperature trends are noticed during the DJF season at the polar regions. Added to that, lowest temperatures (colder than around -85^0 C) occurred starting from oceanic regions to western longitudes during the DJF season at the tropics, indicating a significant water vapor transport from the troposphere into the stratosphere in these regions during the winter season [23] and such similar trends are also identified during 2008-2013 that are shown in the figures from 6a-6d to10a-10d.

Several tropopause theories have been proposed over the years that include radiative and convective processes [14], [19], organized deep-convection and equatorial waves in the tropics [25] and baroclinic eddies in the extratropics [31]. In order to explore the exact relation between seasonal trends of troops and convective activities at the tropics, we have plotted seasonal trends of out-going long radiation (OLR). Figure 11 shows seasonal variations of OLR during different seasons, including March equinox, the June solstice, September equinox, and December solstice (left to right panels) between 2007-2012 (top to bottom panels). It is clear that climatological OLR exhibits localized maxima over Africa, southeast Asia and both eastern and western Pacific regions during March and September equinox seasons and over Africa, southeast Asia and both eastern and western Pacific regions, and over Atlantic regions during June and December solstice seasons. It is, therefore, clear that no specific relation is found to be observed between tropical tropopause and OLR trends, indicating that the tropical tropopause is not solely controlled by localized deep convection and it is expected that waves also play a role. It may be worth to mention here that it has been understood well that other processes such as convectively driven waves [6] also play a significant role in setting the tropical tropopause [15].

With a view to verify tropopause heights, we have presented them in the following section. Figure 12 shows monthly variations of tropopause heights from March 2007 to March 2013 between 60^0 S and 60^0 N latitudes. Although tropical tropopause heights are showing nearly constant trends, the highest values are noticed during the northern winter months (December solstice) in the deep tropics during different months during 2007-2012. Further, strongest gradients in temperature occur between ~30^0 and ~40^0 on both hemispheres.

4. CONCLUSION

The launch of COSMIC GPS RO technique has opened new avenues to study the global atmosphere with relatively higher resolution from the surface of the Earth to an altitude of 800 km. By effectively utilizing huge database available from COSMIC satellites, we have made an attempt here to present long-term trends of tropopause both seasonally and monthly during 2007-2013. In this context, several important results are observed and some of them are presented hereunder.

1) Validation studies of both temperatures and pressure trends at individual locations and over the global between COSMIC retrieved, nearby radiosonde measured and provided by the National Centers for Environmental Prediction re-analysis (NCEP) reveal a good agreement between them, however, with a very few exceptions.
2) Both seasonal and monthly trends are qualitatively quite similar to trends that observed by earlier researchers with COSMIC RO technique. Though both equinox seasons (March and September) are shown with nearly equal trends, a systematic difference is observed between June and December solstice seasons.

3) No specific relationships between tropical tropopause and outgoing long-wave radiation (OLR) trends during different seasons, indicating that the tropical tropopause is not solely controlled by localized deep convection and it is expected that convectively generated waves might play a role.
4) Although tropical tropopause heights show nearly constant trends, the highest values are noticed during the northern winter months (December solstice) in the deep tropics during different months during 2007-2012.

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Figures

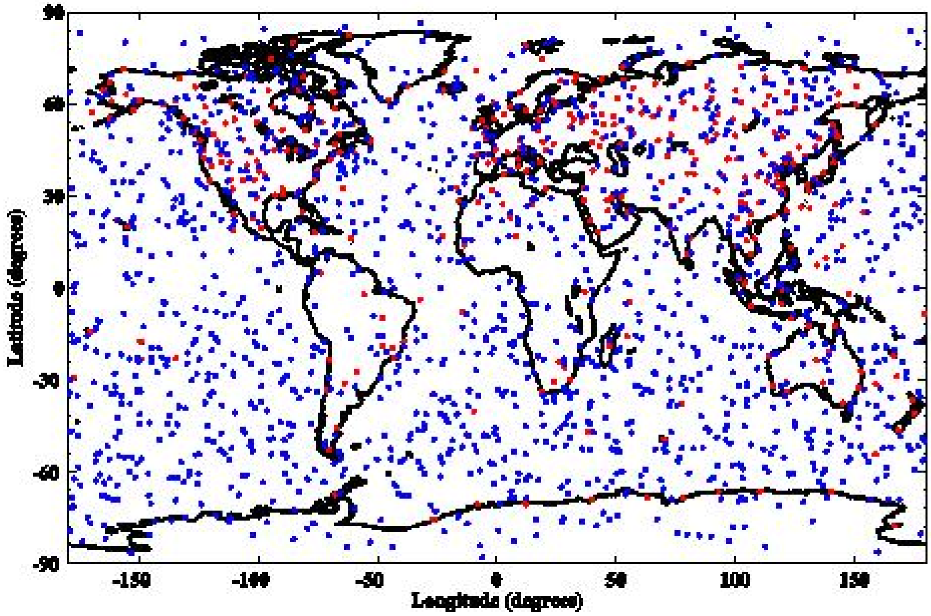

Fig. 1. Global occultations (1465 in number) made by COSMIC satellites (blue circles) and number of radiosonde locations (667 in number) (red circles) on 01 March 2007.

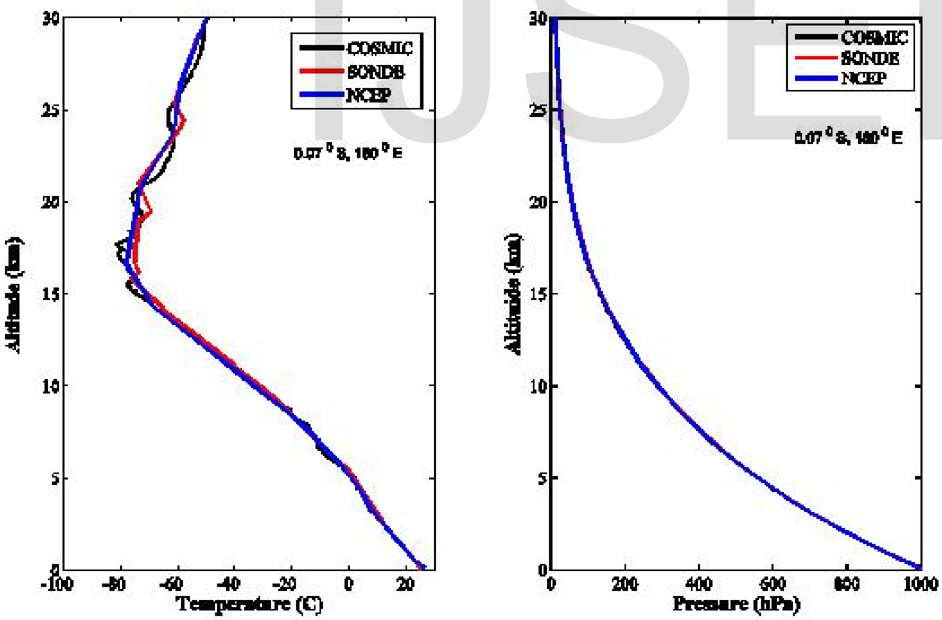

Fig. 2. Left (right) panel shows vertical temperature (pressure) profile measured by COSMIC, near-by radiosonde and provided by NCAR-NCEP reanalysis data on 01 March 2007. See text for remaining details.

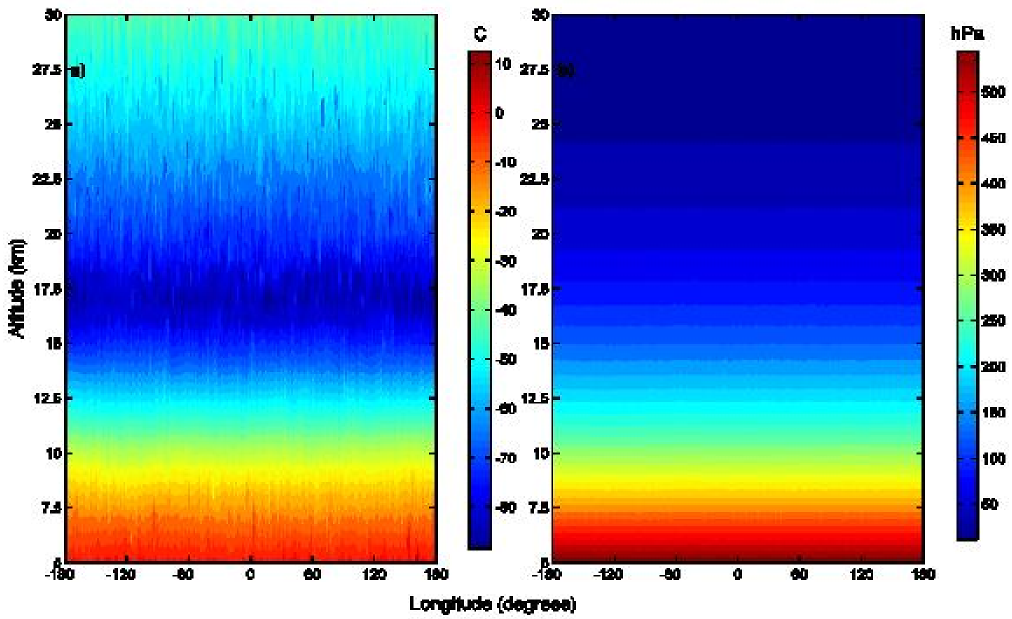

Fig. 3. Global vertical profiles of a) temperature and b) pressure during March-May 2007 averaged between 5^0S-5^0N.

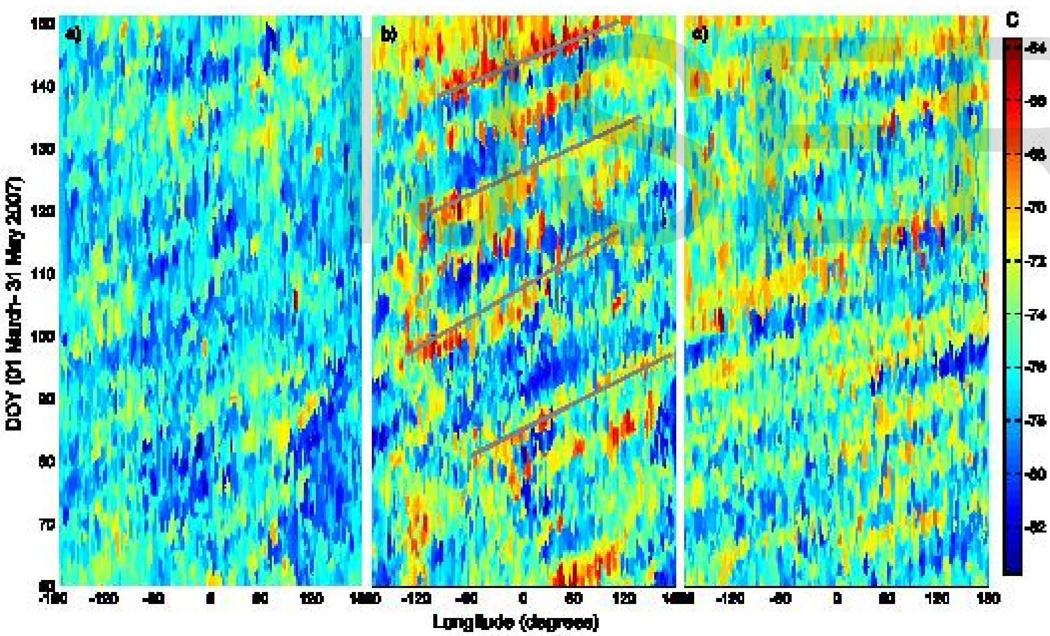

Fig. 4. Global temperature trends during March-May 2007, averaged between 5^0 S-5^0 N, at a) 15 km, b) 17 km, and c) 19 km.

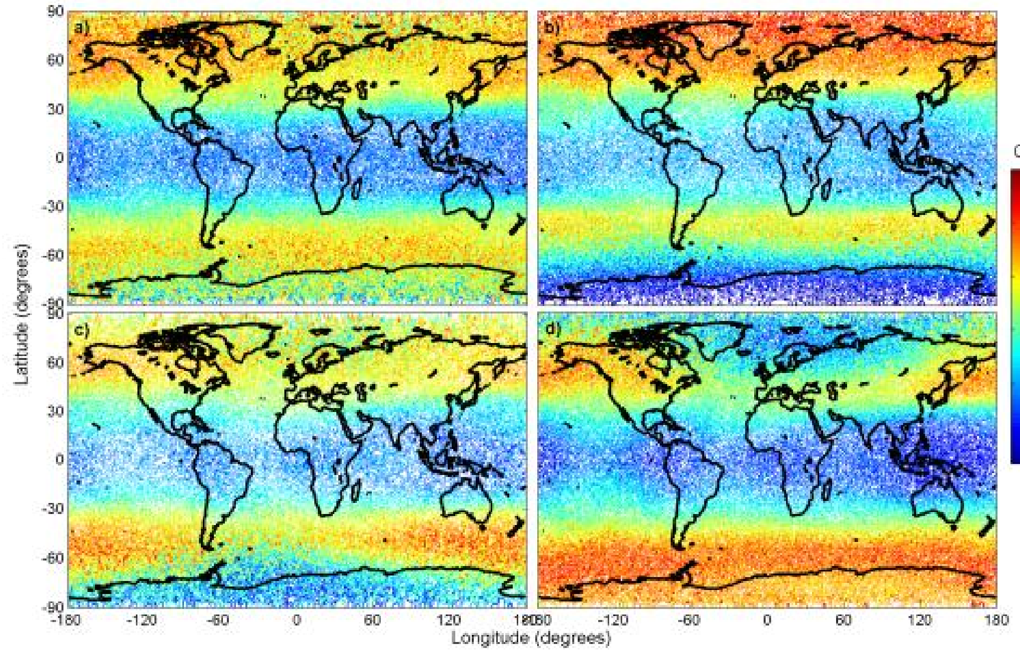

Fig. 5. Global tropopause variations during a) MAM b) JJA c) SON and d) DJF seasons in 2007

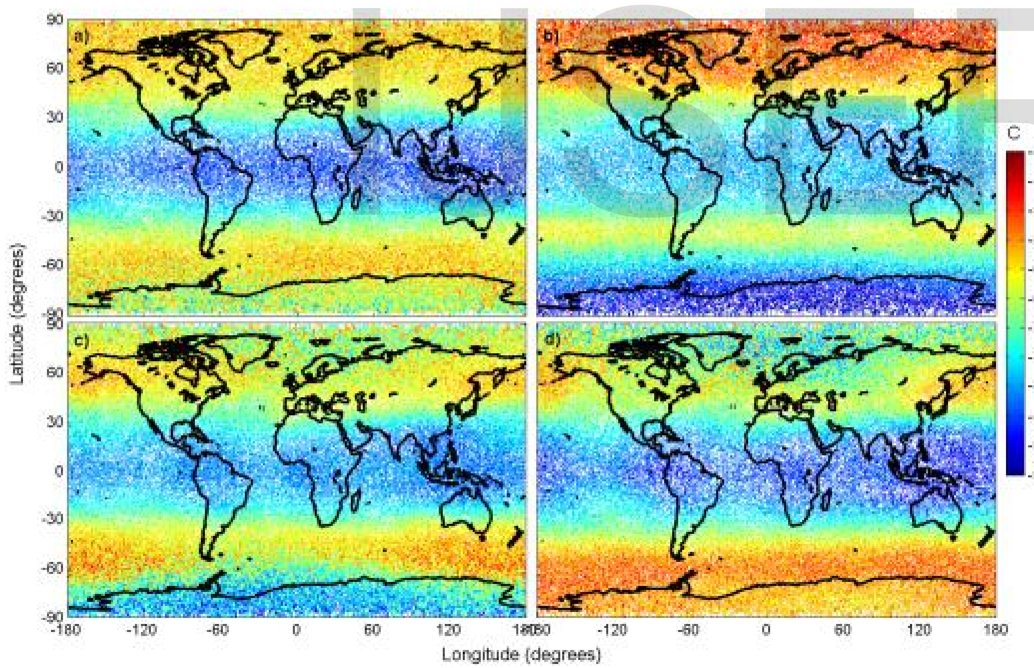

Fig. 6. Global tropopause variations during a) MAM b) JJA c) SON and d) DJF seasons in 2008

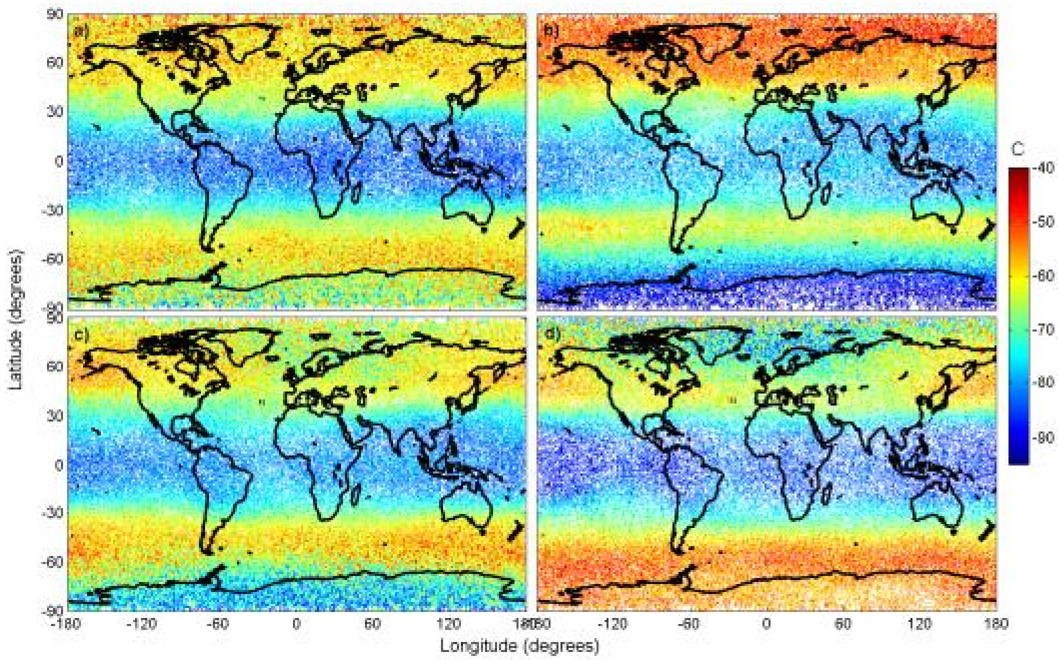

Fig. 7. Global tropopause variations during a) MAM b) JJA c) SON and d) DJF seasons in 2009

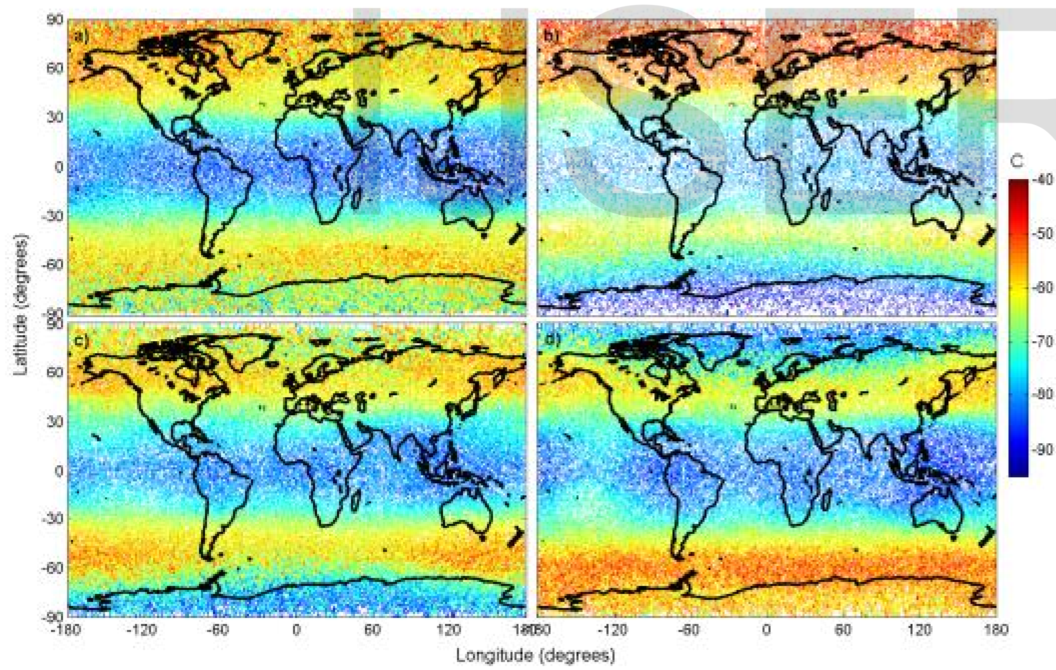

Fig. 8. Global tropopause variations during a) MAM b) JJA c) SON and d) DJF seasons in 2010

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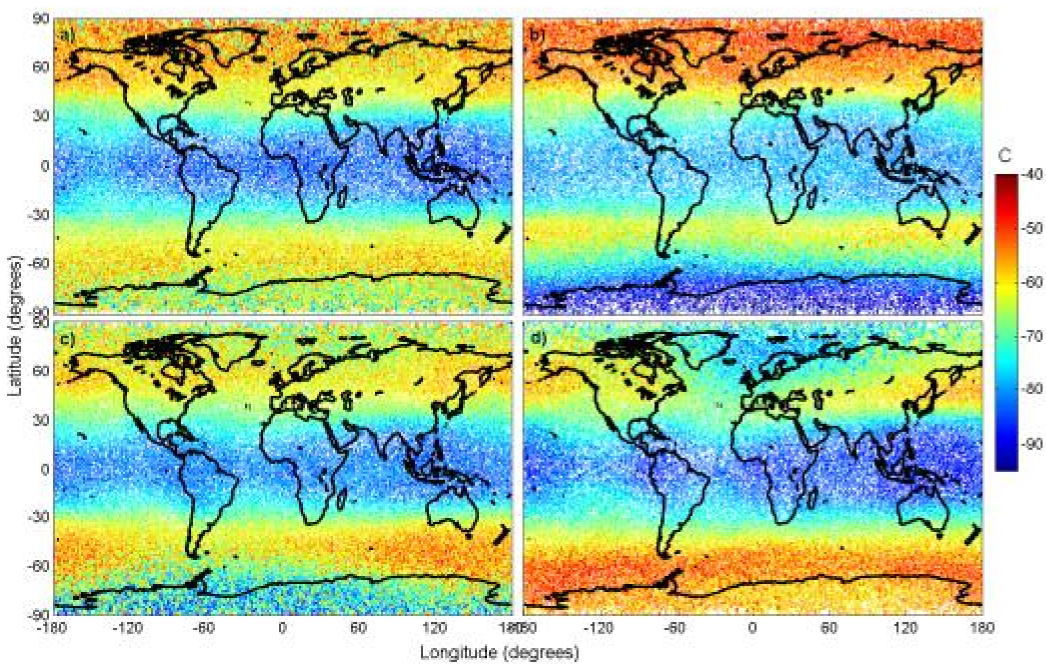

Fig. 9. Global tropopause variations during a) MAM b) JJA c) SON and d) DJF seasons in 2011

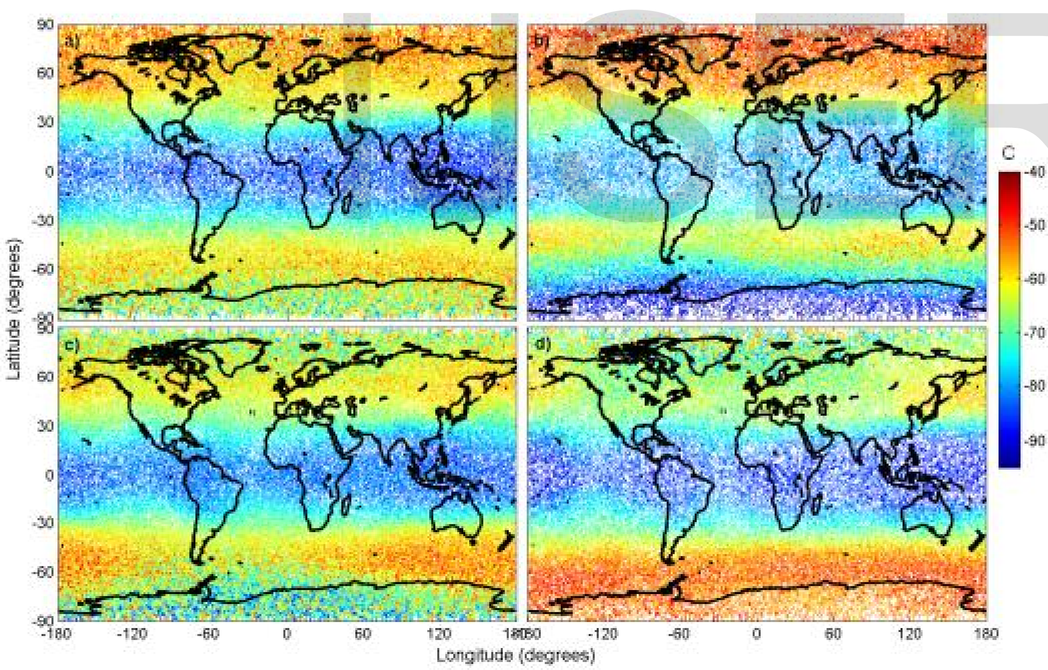

Fig. 10. Global tropopause variations during a) MAM b) JJA c) SON and d) DJF seasons in 2012

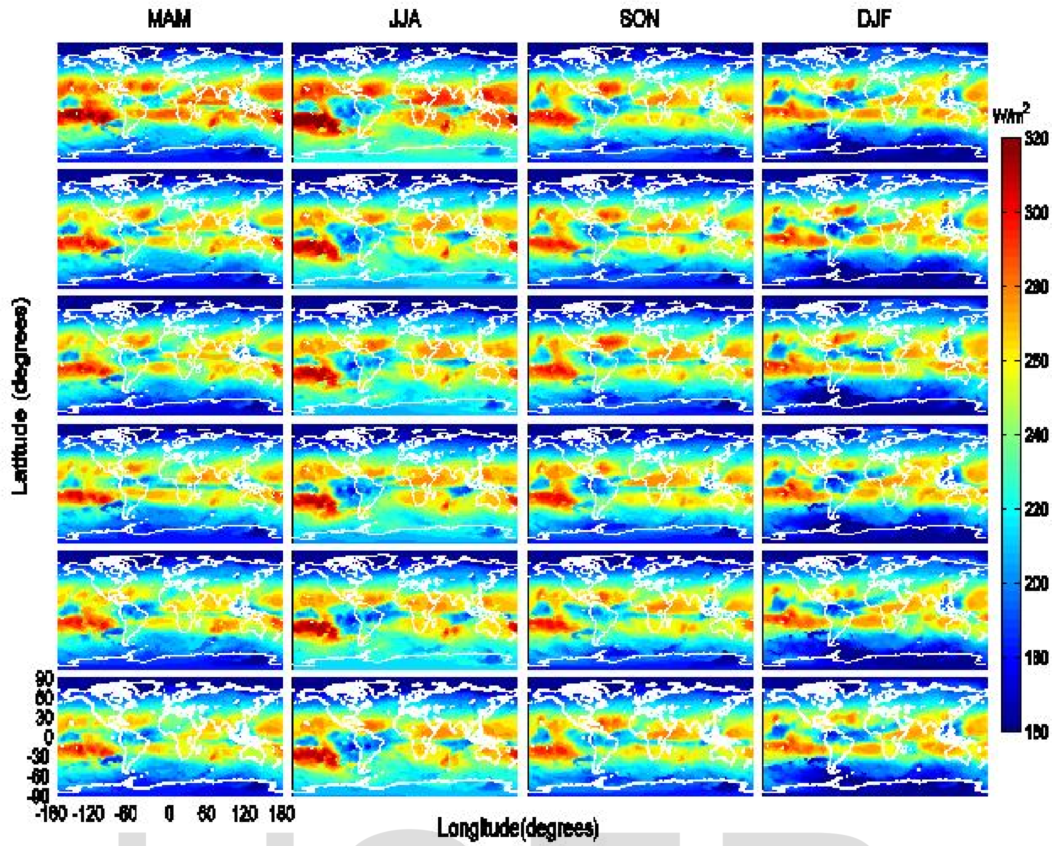

Fig. 11. Different seasonal (MAM- March equinox, JJA- June solstice, SON- September solstice, and DJF- December solstice) variations of OLR from 2007 to 2012

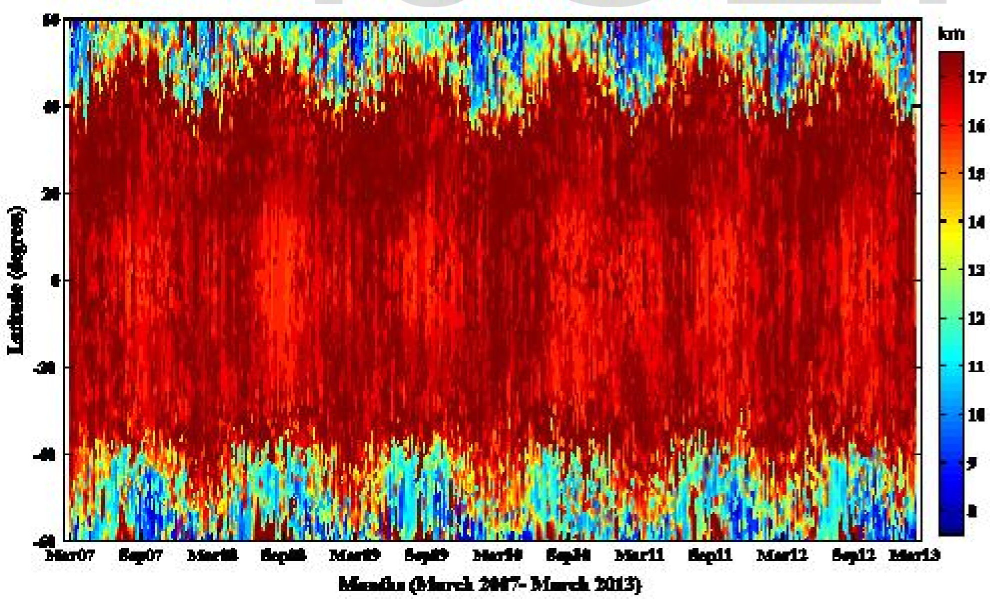

Fig. 12. Month vs. latitudinal variations of tropopause height (km) between 80^0 E and 120^0 E longitude sector