CHAPTER – 4

Global cold point tropopause trends measured using COSMIC radio occultation technique during 2007-2012
4.1 INTRODUCTION

The point of reference structure of tropical CPT, a thermal boundary that often uses to distinguish the bottom of the stratosphere and the top of the troposphere regions of the Earth’s atmosphere, has been recognized to play an important role in stratosphere–troposphere coupling and exchange (Holton et al., 1995). Vaporous transport by convection phenomena from the troposphere in to stratosphere and associated temperatures across CPT may tend to control the thermodynamics of this structure. As the air parcels cross stratospheric threshold, tropical tropopause undergoes freeze-drying process near CPT where vaporous state in stratosphere is influenced by thermal characteristics of CPT (Holton et al., 1995; Mote et al., 1996).

Further, it has been well noted that vaporous state changes in stratospheric region brings in changes pertaining to lower climate by changing global radiation budget (Holton et al., 1995; Forster and shine, 1999). In addition, identification of changes over a longer interval of time in global tropopause based on human induced factors on anthropogenic warming and stratospheric ozone depletion serves as a ‘finger print’ of global climate change by considering the increase in atmospheric pressure across global tropopause with a decrease in its height (Santer et al., 2003a, b). These important implications necessitate accurate study of its structure and long term behaviour of tropopause.

The physical properties of CPT have been reported in the literature by analysing radiosonde measured temperature profiles based on the availability of records for the last seven decades at many tropical locations and also due to their capability in offering in-situ, high-resolution spatio-temporal sampling of vertical temperature and moisture structures (Seidel et al., 2001; Zhou et al. 2001a, Randel et al., 2003; Seidel and Randel, 2006). Although a clear picture on large-scale structure such as latitude-longitude structure of global tropopause may not be possible, certain important aspects have been revealed by radiosonde measurements. As an example, it was confirmed unambiguously that tropopause altitude reaches its highest altitude over tropics, drops suddenly across subtropical jet and lees minimum at lower altitudes in extratropics. Further, although reanalysis datasets including ECMWF 40 Year Reanalysis (ERA-40) and National Center for Environmental Protection – National Center for Atmospheric Research (NCEP-NCAR) Reanalysis (NNR) are available to the scientific community as alternatives, questions have been raised on their quality and coarse vertical resolutions (Santer et al., 2003b; Birner et al., 2006; Kishore et al., 2009).

With the advent of GPS-RO technique, it became possible to collect global temperature and pressure profiles to conduct reliable observational analyses pertaining to physical properties of the
cold point tropopause and to present quantitative and comprehensive results to the research community. Demonstrated accuracy of results from temperature profiles using these techniques are showed by many of the researchers in UTLS region (Nishida et al., 2000; Randel et al., 2003; kim et al., 2012). Yet, as stated by Kim and Son (2012), it is important to study long term interannual variability and trends of the cold point tropopause, as their interannual variability is interrelated to QBO (e.g., Zhou et al., 2001; Randel et al., 2003; Schmidt et al., 2004) and ENSO (e.g., Zhou et al., 2001a; Randel et al., 2000 for lapse rate tropopause) in addition to understanding of stratospheric vapor and UTLS processes.

This chapter begins with presentation of relevant literature survey and global database coverage of radiosonde stations and COSMIC GPS RO technique followed by a comparison between temperature and pressure profiles during March equinox season in 2007 and tropopause seasonal trends from 2007 to 2012 as well as monthly variations of CPT between 2007 and 2012 with conclusions at the end.

4.2 LITERATURE SURVEY

Brewer (1949) explained the existence of a circulation based on observed distributions of helium as well as vapor and ignoring the concept of radiative equilibrium in the stratosphere, in which air enters stratosphere at equator, where it can be desiccated by means of condensation and voyages towards temperate polar regions and finally plunge into troposphere that can warm air across CPT.

Manabe and Strickler (1964) computed thermal and radiative equilibrium of stratosphere by considering gassy absorbers (vapor, carbon dioxide, ozone) consequences and found that atmosphere in pure radiative and thermal equilibrium has tropopause at approximately 10 kilometres at 332.3k and 13 kilometres at 300.3k respectively using average insolation and the pure radiative equilibrium of an atmosphere without solar absorption, but with a fixed temperature at the Earth’s surface is observed to be 289K with an inversion of temperature just above the level of tropopause while the net influence of pole to equator variation of various absorbers on the height of the tropopause in thermal equilibrium is found to be 3.5kilometres, which is not large enough to explain quantitatively the latitudinal variation of the tropopause. Further, their results also showed that the computed temperature of the winter polar stratosphere decreases with increasing altitude without any inversion and clear cut tropopause.

Newell and Gould-Stewart, (1981) suggested methods aimed at substantiating existence of “Stratospheric Fountain”, where air enter stratosphere from troposphere based on an analysis of universal 100mb monthly-mean temperatures. Their calculations are based on the temperature
threshold from observable global stratospheric water mixing ratio that fulfills prerequisite to conserve small stratospheric humidity, while observations showed occurrence of spout over western tropical Pacific, northern Australia, Indonesia and Malaysia in November-March period and over Bay of Bengal as well as India during Monsoon. This study mentioned that major portion of stratospheric air enters through these areas with an exchange in November-March period.

Held (1982) made an attempt to provide a qualitative theory for the height of the tropopause and tropospheric static stability that doesn’t require detailed info on vertical structure of dynamic heating by assuming that lapse rate is independent of height within troposphere so that tropopause height can be expressed as a function of lapse rate. However, the utility of resulting theory is limited by this assumed form of temperature profile.

In 1980’s, JPL (Jet Propulsion Laboratory) proposed monitoring of Earth’s atmosphere by GPS signals and in 1990’s UCAR (University Corporation for Atmospheric Research) along with JPL successfully renewed economic geodesical ground receiver to hover over planet for occultation data collection. Their observations had showed that Doppler shift in GPS signal due to atmospheric bending allowed precise valuation of atmospheric refractive index while Melbourne et al. (1994) presented the significant advantages of utilizing space borne GPS RO products for advanced studies related to observation of the Earth’s atmosphere to gain more understanding.

Holton et al. (1995) made several arguments that are essential to include stratosphere-troposphere exchange (STE) within a global-scale dynamical perspective to distinguish between the part of the atmosphere whose isentropes lie entirely above the tropopause (the over world, $\Theta \geq 380$ K) and the part of the atmosphere whose isentropes span the troposphere and the lowermost stratosphere. When viewed from this global perspective and on seasonal and longer timescales, STE is controlled not by local events near the tropopause, but by the generation of large as well as small scale waves in troposphere suggesting that it would be necessary to compile statistics on the climatology of exchange by individual tropopause folding events and by cut off cyclones corresponding to the lowermost meridional transport by eddy motions.

Mote et al. (1996) described tape recorder hypothesis using explanations of tropical stratospheric vapor showed indication of large scale rising advection like a gesture recorded on an upward moving magnetic tape using yearly fluctuations in actual “entry mixing ratio” of air inflowing tropical stratosphere. Their observations showed methodical phase-lag with respect to annual cycles of respective parameters at higher altitudes in agreement with calculations for validation in addition to
identification of substantial smaller annual variation due to QBO through large-scale upward advection speed (tape speed) which retards signal arrival by 1-2 months in mid-stratosphere.

Kursinski et al. (1997) developed theoretical estimates of the spatial coverage, resolution and accuracy of GPS radio occultations derived from the satellite network to study atmospheric profiles by considering geometric interference in defining vertical range of observations and their resolution which includes error analysis treatise regarding spacecraft radio occultation technique using analytical simulation methods to establish baseline exactitude for retrieved profiles of refractivity, geopotential as well as temperature parameters while vertical resolution database ranges from 0.5-1.4 kilometres from lower troposphere to middle atmosphere showing accurate refractivity profiles can be obtained from -60 kilometres altitude with respect to surface by excluding less than 250 metres in vertical extent associated with high vertical humidity gradients. Further, depending on phase of the solar cycle, sub-Kelvin temperature accuracy can be predicted up to -40kilometres above 250k elevation level in troposphere where water effects are negligible whereas below 250k level, polysemy of water and dry atmosphere refractivity enhances thereby degrading temperature precision.

Highwood and Hoskins (1998) examined the physical meaning of different definitions of tropical tropopause from different atmospheric data sources as well as model outputs and identified little physical relevance for conformist lapse-rate explanation of tropopause in tropics. Based on observations from ECMWF analyses, the properties of annual cycle revealed a relationship with ultratropical stratospheric wave pump in the zonal mean picture, although there exists zonal asymmetries that includes relatively low pressure and temperature at tropopause near west Pacific heating region during DJF (December-January-February) and a conspicuous region with low pressure on tropopause over India during JJA (June-July-August). The consequences are confirmed using baroclinic model by imposing adiabatic thawing, so that both these features can be attributed to direct response of atmospheric large-scale region of tropospheric adiabatic heating, suggesting that stratospheric pump can provide depiction of UTLS region while tropospheric convection remains vital to understand zonal asymmetries within this region.

Forster and Shine (1999) exemplified the ambiguity by distinguishing between radiative forcing and climate feedbacks, stating that changes due to methane oxidation should be viewed as forcing while temperature alterations across tropical tropopause reprise either due to human-induced climate changes or natural variability to be viewed as a feedback similar to changes in tropospheric vapor and ozone changes in stratosphere due to carbon dioxide changes in temperature or circulation, so
that sensitive stratospheric vapor can drive momentous vicissitudes in troposphere by adjusting global radiation budget.

Seidel et al. (2001) presented spatio-temporal depiction of tropical tropopause using 83 radiosonde data stations and computed climatology for 1961-1990 at three echelons that is conventional lapse-rate tropopause (LRT), CPT and 100 hpa levels by comparing their respective averages seasonally and interannually over temperature, pressure, height, vapor saturation mixing ratio and potential temperature. Their observations revealed that during the Northern hemisphere (NH) winter, the tropopause is found to be higher, colder and at lower pressure than southern hemisphere (SH) while a reverse pattern during the NH summer.

Zhou et al. (2001) used radiosonde archives from 1973-1998 to determine the characteristics of CPT and found a cooling trend of about -0.57+0.06 K Decade\(^{-1}\) in tropical temperatures indicating that tropical CPT trends are not influencing stratospheric vapor increase, which is contrary to what has been hypothesized regarding observed stratospheric trends earlier (mid-1990's) and convinced with the same long before in mid-1990’s. Their hypothesis is supported by illustrative calculations and suggested to consider long term changes in tropical convection occurrence frequency and strength to explain cooling trend of CPT temperatures while proposing observed trend in stratospheric vapor may be due to vicissitudes in atmospheric dynamics.

Santer et al. (2003a) showed that both stratospheric cooling caused by ozone and tropospheric warming due to well mixed greenhouse gases lead to increase in tropopause height by several hundred meters since 1979 based on climate model experiments with reanalysis data sets, which revealed human-induced changes account for 80 percent of simulated rise in tropopause height during 1979-1999. This model predicted positive detection given rise to a conclusion that global tropopause loft fluctuations are due to amalgamation of predominant anthropogenic and natural external forcings.

Santer et al. (2003b) tested tropopause height vicissitudes by diagnosing LRT pressure using reanalyses data sets (NCEP besides ECMWF) with integrations from coupled as well uncoupled climate models over period 1979-2000 and observed tropopause altitude enhancement. Further, their simulations indicated that decad changes are thermally driven based on integrated measure of anthropogenically forced warming in troposphere and cooling of stratosphere due to ozone depletion. Their simulation results are in good agreement with earlier results.

Seidel and Randel (2006) inspected and presented synoptic global tropopause inconsistency on monthly, seasonal and multi decadal periods using 1980-2004 radiosonde data, which showed that
their altitude levels are ascending at all stations with an estimated global trend of $64\pm21\text{ mdecade}^{-1}$, tropopause pressure trend of $1.7\pm0.6\text{ hPadecade}^{-1}$ and temperature decrease of $0.41\pm0.09\text{ Kdecade}^{-1}$, along with substantial stratospheric cooling and slighter tropospheric warming while these trends are spatially correlated to stratosphere and uncorrelated to troposphere with respect to temperature. The relationship between tropopause elevation and stratospheric temperature tendencies in association with QBO suggests that, at low frequencies, tropopause is mainly united with stratospheric temperatures thereby revealing that studies related to their long haul may carry sporadic data than suggested by previous studies.

Birner et al. (2006) carried out a study based on a query regarding tropopause inversion layer (TIL) extension in recent general circulation models (GCMs) and meteorological analyses using NCEP/NCAR reanalysis data and Canadian Middle Atmosphere Model (CMAM) which revealed weak existence of TIL in NCEP/NCAR reanalysis data while realistic strength of it in CMAM observations, but much weaker TIL in data assimilation mode in southern hemisphere (SH) thereby concluding that the discrepancy between the analyses and circulation models is attributed to data assimilation that acts to flat shrill structures of temperature around tropopause.

Son et al. (2007) showed tropophilous variability of zonal mean tropical tropopause height moderated by means of localized tropical convection, identified to be part of Madden-Julian oscillation (MJO). Their observations showed that copious circulation response to convective heating warms tropical troposphere and cools lowest tropical stratosphere confined over Pacific warm pool. Further, they have identified those changes in temperature fields have led to increase in tropical tropopause at maximal longitudes within 10 days of convective heating maximum.

Son et al. (2009) examined the advancement of tropopause vicissitudes in past, present and future climatology by analysing long term integration reserve with stratosphere resolving chemistry climate models (CCMs) and forecasted that tropopause pressure will descend while its height will ascend with a trend feebler than recent past whereas forecasted declinational tropopause is observed to be associable with stratospheric ozone recovery which transpires in SH lower stratosphere of CCMs that indicates comparative warming in twenty first century exhibiting their undersize with respect to typical Intergovernmental Panel on Climate Change Fourth Assessment Report (IPCC-AR4) models, specifically in southern high latitudes, suggesting realistic representation of stratospheric processes might reveal reliable deduction on tropopause trends.
4.3 GLOBAL DATA BASE

Although several extensive studies have been carried out for more than decades, CPT topography still remained uncertain. To a large extent, this is mainly due to information inadequacy in UTLS region. In fact, most of the above mentioned studies are based on radiosonde and reanalysis data. These data can neither provide instantaneous spatial coverage nor high vertical resolution in the UTLS region. Specifically, CPT scrutiny via reanalysis data adopts fixed pressure level (around 100hpa), leading to inaccurate tracking of thermodynamic parametric variations whereas according to Zhou et al., (2001), this approach introduces high pressure bias around 7hpa, warm temperature bias around 2K besides over reckoning saturation water vapor mixing ratio around 1.3ppmv. But, according to Ohring et al. (2005), if the biases surpass 0.04 Kdecade$^{-1}$, climate trend detection may be vetoed.

Recently, more reliable observational analyses are under operation that had been enabled by GPS technology incorporating radio occultation technique to attain accurate measurements. These measurements provide fine scale profiling of temperature throughout geosphere instantaneously with effective plumb resolution. By means of temperature profiling derived from earlier satellite missions, researchers have shown that accurateness of temperature profiling from GPS-RO measurements is quite conformable with radiosonde observations in UTLS region, demonstrating their usability in examining the thermodynamics of CPT trends.

![Global occultations](image)

**Figure 4.3.1** Global occultations (1465 in number) made by COSMIC satellites (blue circles) and number of radiosonde locations (667 in number) (red circles) on 01$^{st}$ March 2007.
Figure 4.3.1 presents global operational network coverage of different types of radiosondes along with COSMIC GPS RO that are available as on 1st March 2007 to better inform their use in characterizing cold point tropopause trends. The occultations made by COSMIC satellites are indicated with blue circles which are 1465 in number and the locations of instrumental radiosonde stations are indicated with red circles which are 667 in number. One can understand from Figure 4.3.1 that the number of occultations is extremely high for the latitude sector 80°S- 80°N, which is due to elevated proclivity of COSMIC micro-satellites (78°), while supervision of equatorial region is relatively low above latitudinal range in addition to low precise coverage near Polar regions (80°-90°).

4.4 COMPARISON OF CPT TRENDS

As mentioned earlier, previous studies have inferred changes to the thermodynamic structure of the tropical CPT through the use of sounding and reanalysis data as well as from climate models. Here, by effectively utilizing additional database from COSMIC mission and updated studies, in particular, we have analysed location specific and seasonal specific CPT trends. The experiential physiognomies are then deliberated in association with global tropopause trends using radiosonde, COSMIC GPS RO and NCEP reanalysis data for the period 2007-2013. Although the present observational analysis has shown significant differences, the overall results are in good agreement with earlier results as shown below.

4.4.1 LOCATION SPECIFIC TRENDS

Figure 4.4.1.1 Left (right) panel shows vertical temperature (pressure) profile measured by COSMIC, nearby radiosonde and provided by NCAR-NCEP reanalysis data on 01 March 2007.
In order to validate variability in CPT altitude with respect to the physical parameters, temperature and pressure, initially we made an attempt to study daily variation by considering vertical temperature and pressure profiles measured by COSMIC, nearby radiosonde and provided by NCAR-NCEP reanalysis data on 01st March 2007 at a selected location (latitude 0.07⁰S, longitude 180⁰E). This variation in altitude of CPT with respect to temperature and pressure is partially attributed to climate vicissitudes at specific locations, particularly those located away from equator. The observed variations are then discussed in connection to examine the strong seasonal dependency of CPT and tropical tropopause over the globe. Here, we strive for aptness of RO data to study long-term CPT trends while determining the physical scale and bases of improbability in competent datasets for tropopause dimensions.

Here left panel in figure 4.4.1.1 shows the temperature profile measurement and the right panel shows pressure profile measurement using data retrieved from nearby radiosonde, COSMIC GPS RO technique and NCEP reanalysis data respectively. A comparative analysis made between temperature and pressure profiles revealed a good correspondence (Brahmanandam et al., 2010; Anisetty et al., 2014) with following few exceptions. The Left panel in Figure 4.4.1.1 shows the temperature profile while right panel in Figure 4.4.1.1 shows pressure profile measured by COSMIC micro satellite (No.06), co-located radiosonde and NCEP reanalysis data at geographic latitude 0.07⁰S, geographic longitude 180⁰E with respect to the COSMIC satellite occultation location on 1st March 2007 between 0 and 30 kilometres, whereas radiosonde measurements were taken at 141 kilometres altitude and 01:45 hours away from the COSMIC satellite location. Obviously, one can notice an existing slight difference in temperatures measured by these three independent observations at 0 to ~8 kilometres altitudinal range due to interference of vapor and few differences in magnitudes of temperature were found in and around the cold point tropopause (CPT), specifically between radiosonde and COSMIC retrieved profiles, showing an observational evidence of earlier studies made by Kishore et al. (2009), Sun et al. (2010), Zhang et al. (2011). As an example, validation study performed by Kishore et al. (2009) using the operational stratospheric analyses including, NCEP, JRA-25 and UKILOMETRESO datasets. The results are in good agreement with previous observed results from COSMIC as well as other reanalysis outputs, with mean global vicissitudes as well as variances in altitudinal range from 8-30 kilometres under 1K while spatial driftage over polar latitudes and altitude-wise at tropical tropopause with dissimilarities being 2-4K. Sun et al. (2010) compared collocated global atmospheric temperature profiles from radiosondes and COSMIC GPS RO from April 2008-October 2009 and found that tropospheric temperature standard deviation errors were 0.35K per 3h and 0.42K per 100 kilometres while Zhang et al. (2011) made comparative studies on GPS-RO temperature profiling from both CHAMP as well as COSMIC
with radiosonde records from 38 Australian radiosonde stations which showed good agreement between the two datasets. To be more specific, Zhang et al. (2011) have found the mean difference of temperature between CHAMP and radiosonde to be $0.39^\circ$ C, while it was $0.37^\circ$ C between radiosonde and COSMIC.

On the other hand, a cent percent consistency in observed magnitudes of pressure is prevalent. In view of this, it is clear that temperature and pressure profiles clearly show good agreement between these three measurements, thereby providing confidence in using COSMIC GPS RO retrieved temperatures in the studies of long-term observation of tropopause trends and atmospheric dynamics.

4.4.2 COMPARISON OF SEASONAL TRENDS

![Figure 4.4.2.1](image)

**Figure 4.4.2.1** Global vertical profiles of a) temperature and b) pressure during March-May 2007 averaged between $5^\circ$S-$5^\circ$N

To identify seasonal trends of cold point tropopause (CPT), we have verified the global trends of both temperature and pressure retrieved from COSMIC and presented them during March equinox season of 2007. In Figure 4.4.2.1, left panel displays temperature profiling while right panel displays pressure profiling averaged between $5^\circ$ S and $5^\circ$ N latitudes, from 5 to 30 kilometres range during March-May 2007. From this figure, obviously temperature trends exhibit decreasing tendencies by means of increasing altitude starting from 5 kilometres to ~17.5 kilometres
(tropopause), known to be the temperature lapse rate and an association of increasing trends with the progress of time from ~17.5 kilometres to 30 kilometres. Also, tropical tropopause is located at ~100 hpa pressure level as can be viewed from the right panel of figure 4.4.2.1 where one can notice decrease in magnitudes associated with pressure with increasing altitude monotonically starting from 5 kilometres to 30kilometres.

When temperature trends are taken into consideration, It is well known that planetary wave structures such as Kelvin waves show significant contribution in modifying temperatures that are present near the equatorial tropopause region (Mote et al., 2002, Randel and Wu, 2005; Ratnam et al., 2006), which can influence structure of tropopause (Tsuda et al., 1994; Randel and Wu, 2005; Ratnam et al., 2006). With a view to verify such wave characteristics, we have made an attempt to plot temperature trends near equatorial tropopause region approximately between 5°S and 5°N in the following lines.

![Figure 4.4.2.2 Global temperature trends during March-May 2007, averaged between 5°S-5°N, at a) 15 km, b) 17 km, and c) 19 km.](image)

Figures 4.4.2.2a-c presents global temperature trends of the equatorial region at 15, 17 and 19 kilometres altitude respectively during March-May 2007. It would be worthwhile to mention here that, although a systematic procedure needs to be implemented to explain Kelvin wave features from derived temperature trends as described in chapter 3, it is also possible to identify Kelvin waves by verifying temperature plots drawn from longitude versus day of the year, so that their inherent features including east-ward propagation and global-scale zonal wavenumbers can easily be observed from these plots. From figure 4.4.2.2b, we can clearly notice that the east-ward
propagating waves are evident at 17 kilometres range, in addition to observation of similar characteristics with lesser magnitudes at 15 and 19 kilometres altitude range in figures 4.4.2.2 a and 4.4.2.2 c. To make it more clearly, we have represented east-ward propagations with inclined snuff colour lines in Figure 4.4.2.2 b. By doing so, one can notice that Kelvin waves are associated with zonal wavenumber-2 with wave periodicities between around 12 and 18 days (slow Kelvin waves). Similar analysis has been made for the remaining seasons to find influence of Kelvin waves on CPT over this six year period (2007-2012) and some of the interesting results are discussed in the following sections.

4.4.3 SEASONAL SPECIFIC TROPOPAUSE TRENDS

We have verified spatial structures of temperatures during different seasons by considering tropopause data for every three month period that are put together as ensembles i.e. 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 study period 2007-2012.
Figure 4.4.3.1 (a-d) presents spatial structures of global tropopause trends during MAM, JJA, SON and DJF seasons during our six year study period 2007-2012. As expected, one can notice that tropical locations are associated with a minimum of around -80°C (195 K) values during different seasons. Yet both equinox terms resemble equal trends (Figures 4.4.3.1 (a) and 4.4.3.1 (c)), a methodical alteration is identified during June and December solstice seasons (Figures 4.4.3.1 (b) and 4.4.3.1 (d)). As an example, northern Polar Regions during JJA season, i.e. northern hemisphere summer are associated with higher temperatures (~50°C) compared to southern Polar Regions (~80°C). In contrast to JJA season trends, reverse temperature trends are identified during DJF seasons at the Polar Regions. In addition, lowest temperatures (> -85°C) has been observed starting from oceanic regions to western longitudes during the DJF season at the tropics, indicating noteworthy vapor transport from troposphere to stratosphere during winter season within these regions (Newell and Gould-Stewart, 1981) besides identification of similar trends during 2008-2012 that are shown in above figures.

Many theories related to several tropopause studies have been proposed over the years that include radiative as well convective processes (Manabe and Strickler, 1964; Held, 1982), organized deep convection in addition to equatorial waves in tropics (Randel et al., 2003) as well as baroclinic eddies in the extra tropics (Son et al., 2007). We have plotted seasonal trends of outgoing long wave radiation to explore the exact relation between seasonal trends of tropopause and convective activities at the tropics.
Figure 4.4.3.2 Different seasonal (MAM- March equinox, JJA- June solstice, SON- September solstice, and DJF- December solstice) variations of OLR from 2007 to 2012

Figure 4.4.3.2 shows seasonal variations of OLR during varied seasons including, March equinox (MAM), June solstice (JJA), September equinox (SON) and December solstice (DJF) when panels are viewed from left to right while top to bottom view presents year wise seasonal variations of OLR during the study period 2007-2012.

Further, it can be clearly noticed that climatic OLR unveils localized maxima over Africa, South east Asia besides 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. Therefore, once again, it is clear that there is no specific relation between observed tropical tropopause and OLR trends, indicating that tropical tropopause is not only controlled by means of localized deep convection but also by atmospheric waves. It would be worthwhile to mention here that it has been well understood that, add-on processes such as convectively driven waves (Brahamandam et al., 2010) also found to be conducive to set tropical tropopause (Highwood and Hoskins, 1998).

With a view to verify tropopause heights, we have studied latitudinal variations on a monthly basis during 2007-2013 and are discussed below with the help of Figure 4.4.3.3.
Figure 4.4.3.3 Month vs. latitudinal variations of tropopause height (km) between 80° E and 120° E longitude sector

Figure 4.4.3.3 presents the monthly variations of tropopause heights from March 2007 to March 2013 between 60°S and 60°N latitudes. The uppermost values are prominent during northern winter months (December solstice) in deep tropics in 2007-2012 while tropical tropopause heights are showing nearly perpetual trends, whereas strongest gradients in temperature are observed between ~30° and ~40° on both hemispheres.