Modulation of the Tropical Tropopause due to Equatorial Waves: Seasonal Variability
7.1. Introduction

Equatorial waves are an important class of eastward (Kelvin waves) and westward (Rossby-gravity) propagating disturbances in the ocean and in the atmosphere that are trapped about the equator (i.e., they decay away from the equatorial region). The phenomenon of the Kelvin waves in the ocean is well known for a long time. In the stratosphere first evidence for Kelvin waves was found by Wallace and Kousky [1968] and Rossby-gravity waves were first detected by Yanai and Maruyama [1966] (therefore Rossby-gravity waves sometimes are called Yanai-waves). Diabatic heating by organized convection can excite atmospheric equatorial waves. Their propagation can cause the effect of convective storms to be communicated over large longitudinal distances, thus producing remote response to localized heat sources. As a consequence in the troposphere there are significant contributions of convectively coupled equatorial waves, directly linked to the convective systems acting as wave sources [e.g., Wheeler and Kiladis, 1999; Straub and Kiladis, 2003; Cho et al., 2004]. For the convectively coupled equatorial waves which are mainly observed in the troposphere (e.g., Wheeler and Kiladis [1999]) the nature of convective coupling determines the phase speed and therefore the vertical scale of the waves. These convectively coupled waves have typical periods of 5-10 days, wave number $k = 2-3$, and a phase speed of $15 \text{ ms}^{-1}$.

Equatorial waves also propagate vertically into the stratosphere. Equatorial waves observed in the stratosphere are dominated by “free mode” wave, which are excited by deep convection in the troposphere but no longer linked with the space-time patterns of the convective forcing [Randel and Wu, 2005]. In the stratosphere, different from the troposphere, in particular the Kelvin waves observed (but also other equatorial wave types) cover a larger range of periods. Therefore, for example, the stratospheric Kelvin waves can be classified as ultra-slow (periods 25–30 days, Canziani, [1999]), slow (periods 10–20 days, Shiotani et al., [1997]), fast (periods 6–10 days, Hitchman and Leovy, [1988]), and ultra-fast waves (periods 3 to 4 days, Salby et al., [1984]; Lieberman and Riggin, [1997]; Garcia et al., [2005]). The free mode waves are mainly observed in the stratosphere. The tropospheric vertical wavelength values can be attributed to the vertical scale of the convective systems acting as source (e.g., Chang, [1976]; Fulton and Schubert, [1985]; Salby and Garcia, [1987]) which is in good agreement with the vertical
scale of the heating. Typical vertical profiles of thermal forcing in convective systems have a broad maximum over about 2–8 km in the troposphere (e.g., Chang, [1976]; Fulton and Schubert, [1985]; Johnson and Ciesielski, [2000]). Both convectively coupled and free mode Kelvin waves can affect the behavior of tropical tropopause and influence the dehydration and cirrus formation [Fujiwara et al., 1998] and occurrence of turbulence [Fujiwara et al., 2003]. The equatorial planetary scales wave modes [Hitchman and Leovy, 1988; Dunkerton, 1997; Baldwin et al., 2001] and small-scale waves play dominant role in deriving the QBO in the stratosphere. As a result of the interaction with the QBO winds tropical wave activity itself shows modulations due to the QBO.

Since the discovery of equatorial waves, numerous studies have been carried out based on radiosonde data [e.g., Angell et al., 1973; Sato et al., 1994], MST Radar and Lidar data [e.g., Krishna Murthy et al., 2002] as well as satellite data providing a global view of the atmosphere. To mention a few studies dealing with stratospheric satellite data are Salby et al. [1984]; Randel et al. [1990]; Randel and Gille [1991]; Bergman and Salby [1994]; Canziani et al. [1994]; Srikanth and Ortland [1998]; Tsai et al. [2004]; Randel and Wu [2005]; and Ratnam et al. [2006]. Due to limitations in the data sets, most of these studies are confined to study of only Kelvin waves without considering much Rossby gravity waves. In addition, many analyses focus on zonal wave numbers 1–2, neglecting the higher wave numbers, which are also important for the modulation of tropical tropopause. Further, using ERA-15 temperature and wind data, Tindall et al. [2006a, b] proved that higher zonal wave number from 4–7 also contribute significantly to the momentum flux of waves around tropopause region. The nature of equatorial waves modulating the tropical tropopause in different seasons and in different regions is yet to be studied. Since COSMIC GPS RO consisting of six satellites, is providing relatively dense number of observations even in the equatorial region, an attempt has been made to investigate the modulation of tropical tropopause by both Kelvin and Rossby waves and extended the analysis to see the waves with wave number up to 9 although most of the effects are seen up to wave number 4.
7.2. Data and Analyses

7.2.1. COSMIC Data

COSMIC GPS-RO (Global Positioning System-Radio Occultation) data for the period of August 2006- August 2008 is used to investigate the equatorial waves and its effect on modulation of tropopause. The details about COSMIC data and GPS RO technique are provided in Chapter 2 and Chapter 6.

7.2.2. Longitudinal Grid

The locations of the occultations observed during August 2008 within ±10° from the equator are shown in Figure 7.1 (top panel). The occultations are approximately evenly spaced with latitude with fewer near the equator. Note that the amplitude of the equatorial waves is centered over the equator with a symmetric Gaussian latitudinal structure, with typical meridional e-folding scales of ~ 15°- 20° latitude [Andrews et al., 1987; Mote et al., 2002]. Bottom panel of Figure 7.1 shows the monthly number of occultations available during the observation period. The monthly numbers of measurements are in the range of 2300 - 4700. Therefore, the 10° S-10° N sampling provides ~ 75-150 measurements per day, approximately evenly spaced in longitude. The data over 10°S-10°N is averaged in 20° longitudinal grids. There are some data gaps especially during months when occultation is less. However, 1-2 data gaps are filled by linear interpolation. The data are prescreened to remove outliers (data outside 3 sigma variance at any level over 10-30 km). Here main interest is to study the seasonal characteristics of the equatorial waves up to the zonal wave number 1 to 4 within different phases of the QBO. The 20° grid averaging will provide 18 points in every altitude and according to Nyquist criteria one can extract the zonal wave number up to 9. The zonal mean temperature anomalies in the temperature in the grid 10°S-10°N latitude and 20° degree longitude are estimated. The temperature anomalies at each altitude are subjected to Fourier analysis amplitude and frequency by applying least square method for each day during August 2006-August 2008. This observation period has been divided into eight seasons, namely, September-November 2006, December 2006-Februaray 2007, March-May 2007, June-August 2007, September-November 2006, December 2007-Februaray 2008 March-May 2008 and -August 2008 represented as SON06, DJF07,
MAM07, JJA07, SON07, DJF08, MAM08 and JJA08, respectively. These notation will be used throughout this Chapter wherever is required.

![Figure 7.1: Locations of the radio occultations occurred during August 2007 within ±10°. Bottom panel shows the monthly number of occultations available during August 2006 – August 2008.](image)

### 7.3. Results

#### 7.3.1. Background wind conditions

The background wind conditions play crucial role in the wave characteristics. Thus, stratospheric QBO plays an important role in delineating the wave characteristics. To know exact nature of the waves, the easterly, westerly and transition phase of the QBO need to be taken into account. In this study, the planetary waves in relation to thermal variability in the equatorial tropopause are characterized in different seasons which are in different phases of QBO. Figure 7.2 shows the altitude-time sections of the zonal mean temperature anomalies (deviations from annual mean cycle) and zonal winds for the period August 2006 to August 2008. The equatorial temperature anomalies derived from COSMIC measurements and zonal wind from the NCEP data are shown in Figure 7.2 (a) and 7.2(b), respectively.
The temperature anomalies and zonal wind over Singapore and Gadanki are also shown in Figure 7.2 (c) and 7.2 (d) and Figure 7.2 (e) and 7.2 (f), respectively. The temperature anomalies shows consistently similar feature in all the three data sets. The temperature anomalies near cold point tropopause altitude show clear annual oscillation with alternate warm anomalies during June-August and cold anomalies during December-February. The zonal wind shows strong variability associated with stratospheric QBO in the equatorial zonal mean NCEP data and over Singapore with descending cold anomalies associated to easterly shear zone during October 2006-April 2008. However, zonal wind over Gadanki is weakly associated with QBO and its effect can be seen above altitude region of ~20 km. The zonal wind at Gadanki shows strong variability associated
with monsoonal tropical easterly jet streams (TEJ) during June-September and westerly during October –April in upper troposphere (~10 km) to lower stratosphere (~ 20 km). There is alternate reversal of zonal wind between easterly to westerly during summer and winter. Here, the characteristic of the equatorial waves and its association with tropical tropopause in different seasons with respect to QBO changes is analyzed.

**Figure 7.3:** Longitude-time diagram of the grided temperature variations over 10°N-10°S observed during different seasons during September 2006-August 2008 at 17 km.

The grided temperature profiles from the COSMIC RO in the altitude range of 10-30 km mentioned above are the basic data for the present study. The temperature anomalies are obtained by subtracting the zonal mean temperature profiles from gridded temperature profiles each day. Figure 7.3 shows the longitude-time diagrams of temperature variations at 17 km observed in different seasons during August 2006-August 2008, constructed from grided temperature anomalies. The 17 km level is near the
tropical cold point tropopause and temperature patterns are quasi-stationary, which is the known climatological structure of cold temperatures over longitudes ~90–180°E associated with maximum convection over Indonesia [e.g., Highwood and Hoskins, 1998; Seidel et al., 2001; Randel et al., 2003].

![Figure 7.4: Same as Figure 7.3 but observed at 19 km.](image)

However, in addition to quasi-stationary wave structure, there are the periods where eastward propagating anomalies are evident, particularly during October 2006, May 2007 and June-August 2008. The fluctuations during these months show periods of ~18 days (October 2006), ~22 days (May 2007), and ~12 days (August 2008). In contrast, the temperature anomalies at 19 km depicted in Figure 7.4 show a zonal wave number 1 structure with regular eastward propagation with a period of ~20 days. The zonal phase speed (from dispersion relation of Kelvin wave, \( c^2 \equiv (\nu/\kappa)^2 \); \( \nu \) = angular
frequency and k = zonal wave number) for period 20 days and zonal wave number 1 is found to be ~ 20 m/s.

7.3.2. Dominant Periodicity for Wave 1-4 Component

Besides the zonal wave number 1, wave number 2, 3 and 4 are also embedded in the anomalies which can be seen clearly from Figure 7.5. Figure 7.5 shows that the anomalies at the cold point tropopause altitude during 18-28 December 2006 (day number 230-240, whish starting with day number 1 from 1 August 2006) fitted with 1, 2, 3 and 4 components of the wave, respectively. In order to bring out the characteristics of the eastward propagating temperature anomalies for different zonal wave numbers, amplitude (A_k) and phase (\phi_k) of the gridded zonal temperature anomalies for each day are calculated by least square method. Later, the time series of isolated dominant wave numbers (k = 2\pi/\lambda_x) are constructed using a sinusoidal fitting function,

$$f(x) = \sum_{k=1}^{4} A_k \sin(k(x - \phi_k))$$  \hspace{1cm} (7.1)

where, x represents the longitude in [-\pi: \pi] in 20° interval.

The sinusoidal fitted time series profiles for each wave numbers at each altitude (in the range 10 to 30 km) for each season are subjected to Fourier analysis which provides the amplitude spectrum in the frequency domain. The Fourier transform \( \mathcal{F}(\omega) \) of temperature T(t) is given by

$$\mathcal{F}(\omega) = \frac{1}{t_0} \int_{0}^{t_0} T(t) \exp(-i\omega t) dt$$  \hspace{1cm} (7.2)

Where \( t_0 \) is the time (in days), \( \omega = 2\pi f \), f (=1/Period of oscillations) is the temporal frequency and \( t_0 \) is the data length in days.

The amplitude and phase of the fitted temperature anomalies for the wave number 1 to 4 are calculated using equation 7.2. The amplitude spectra for each longitudinal grid for a season is obtained, which shows more or less coherent structures. These coherent spectra are planetary in nature. These amplitude spectrums for each longitudinal grid are averaged. The averaged spectra for wave numbers 1-4 represent the dominant periodicity throughout the equatorial belt. The amplitude spectra for the wave number 1-4 in
different seasons are shown in Figures 7.6 to 7.9, respectively. Figure 7.6 shows temporal frequency (period) - amplitude spectra obtained for the zonal wave number \( k = 1 \) during different seasons. The spectra during different seasons in Figure 7.6 shows strong peaks at period from 18 to 23d (T1) which have maximum amplitude over the altitude region above tropopause to 30 km (Z1) as listed in Table 7.1.

![Figure 7.5](image)

**Figure 7.5:** Typical examples of the cold point tropopause altitudes anomalies (deviation from equatorial zonal mean) (blue curve) fitted for wave number 1, 2, 3 and 4 (black curve) respectively, for day number 230-240 (18-28 December 2006, starting with day number 1 as 1 August 2006). Each curve is separated by 5 scale factor.

Two maxima of the amplitude can be seen from Figure 7.6 during JJA07, SON07, DJF08 and MAM08. The maximum at the higher altitude is most prominent during season DJF08. Weak westerly exists in lower stratosphere during September 2006- May 2007 and June2008-August 2008 while easterly appears during June 2007 –May 2008 (Figure 7.10). Although wave period is same \( \sim 18-23d \) in both these phases phases, the wave amplitude is confined to a narrower altitude region during westerly phase when compared to easterly phase of the QBO which is clear from Figure 7.10 (a). It is
interesting to note that the transient wave doesn’t, in general, strongly extend down to tropopause altitudes (shown as horizontal lines in figure and values are listed in Table 7.1) or below. However, there are the seasons such as SON06 and MAM07 during which the waves extend down to tropopause altitude, consistent with Figure 7.3(a) and Figure 7.3 (c), respectively.

**Table 7.1:** The dominant periods ($T_1$ and $T_2$) and their altitude of occurrence ($Z_1$ and $Z_2$), the corresponding wavelength for $T_1$ and altitude of cold point tropopause for the wave number 1 are listed for different seasons.

<table>
<thead>
<tr>
<th>Season</th>
<th>$T_1$</th>
<th>$Z_1$</th>
<th>$T_2$</th>
<th>$Z_2$</th>
<th>$\lambda_z$</th>
<th>$Z_{CPT}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>SON06</td>
<td>~18d</td>
<td>~16-23 km</td>
<td>~12d</td>
<td>~23 km</td>
<td>~5-6 km</td>
<td>16.9 km</td>
</tr>
<tr>
<td>DJF07</td>
<td>~18d</td>
<td>~18-20 km</td>
<td>~10d</td>
<td>~22 km</td>
<td>~4-5 km</td>
<td>17.5 km</td>
</tr>
<tr>
<td>MAM07</td>
<td>~23d</td>
<td>~16-19 km</td>
<td>~9-12d</td>
<td>~21 km</td>
<td>~3-5 km</td>
<td>17.4 km</td>
</tr>
<tr>
<td>JJA07</td>
<td>~18-23d &amp; ~23d</td>
<td>~17-20 km &amp; ~21-26 km</td>
<td>~12d</td>
<td>~17-30 km</td>
<td>~6-7 km</td>
<td>17.0 km</td>
</tr>
<tr>
<td>Son07</td>
<td>~23d</td>
<td>~17-20 km</td>
<td>~10d</td>
<td>~19 km &amp; ~28 km</td>
<td>~6-7 km</td>
<td>17.0 km</td>
</tr>
<tr>
<td>DJF08</td>
<td>~18d</td>
<td>~17-20 km &amp; ~22-26 km</td>
<td>-</td>
<td>-</td>
<td>~6-7 km</td>
<td>17.5 km</td>
</tr>
<tr>
<td>MAM08</td>
<td>~23d</td>
<td>~17-19 km &amp; ~21-25 km</td>
<td>-</td>
<td>-</td>
<td>~6 km</td>
<td>17.4 km</td>
</tr>
<tr>
<td>JJA08</td>
<td>18-23d</td>
<td>~17-19 km</td>
<td>-</td>
<td>-</td>
<td>~3-4 km</td>
<td>16.7 km</td>
</tr>
</tbody>
</table>

Another interesting observation is that the wave periodicity less than 10 days does not exist in the wave number 1 spectrum. There are another class of spectral peaks with shorter period ~9-12 days ($T_2$) in the altitude region $Z_2$ listed in Table 7.1. Note that the wave number 1 is hardly dominant below the tropopause region. In contrast, wave numbers 2, 3 and 4 exists only in and around the tropopause region. From Figures 7.7 to 7.9, it is clear that wave number 2, 3, and 4 spectra with period ~ 5-20 days (the periodicity less than 5 days is not considered in the present analysis) are confined to the region ~ 15-20 km. Interestingly, these frequency-amplitude spectrums are observed to be located in the region of westerly shear zones [Figure 7.10 (b)].
7.3.3 Amplitude and Phase Characteristics of Wave numbers 1 to 4

The vertical structures of the amplitude of the waves for wave number 1 of the periods T1 (~ 18-23d) (underlined values in case of range) listed in Table 7.1 during different seasons are shown in Figure 7.11. These features show the characteristics of the Kelvin wave (eastward phase tilt with height) with coherent vertical structures and large amplitude near and above the tropopause (indicated by dot in each panel). However, the amplitude decreases sharply by a factor of ~3-4 away from the altitude range of these maximum amplitude zones. It is worth to mention that there is significant depression of the tropopause altitude (~ 600 m) near ~ 60°E associated with the Kelvin wave during JJA07 and JJA08. As mentioned earlier, the maximum wave amplitude is confined to

Figure 7.6: Altitude profiles of zonal wave number 1 space time spectra calculated from gridded COSMIC data for different seasons during August 2006-August 2008. Black line represents altitude of cold point tropopause.
narrower regions for the seasons during the westerly phase of the QBO when compared to the season falling in the easterly phase of the QBO.

![Figure 7.7](image)

**Figure 7.7**: Same as Figure 7.6 but observed for zonal wave number 2.

The coherent zonal structure of the amplitude shows two symmetric shapes. These symmetric shapes of the amplitude maxima are most evident near and above the tropopause altitudes and show different structures during different seasons which are pronounced during easterly phase of the QBO in comparison to westerly phase of the QBO. The centers of these symmetric shapes are separated by 180°. Figure 7.12 shows the eastward phase propagation of the Kelvin wave corresponding to the amplitude shown in Figure 7.11. The height-longitude variations in the phase for the wave number 1 and period T1 shows the characteristics of tilted constant phase. This phase systematically progresses (grows) as one move from west longitude to east longitude at given altitude in the lower stratosphere.
Figure 7.8: Same as Figure 7.6 but observed for zonal wave number 3.

Figure 7.9: Same as Figure 7.6 but observed for zonal wave number 4.
Figure 7.10: (a) The seasonal mean zonal wind and (b) the vertical shear of horizontal wind observed over Singapore during different seasons.
Therefore, constant phase tilt can be described as; the constant phase starts at lower altitude at west longitude (180°W) and end at higher altitude at east longitude (180°E). The vertical wavelength can be obtained as altitude difference between any two consecutive constant phase lines. The measured vertical wavelength ($\lambda_z$) is also listed in Table 7.1. It is seen that the vertical wavelength is shorter during westerly phase of the QBO (~3-6 km) in comparison to easterly phase of the QBO (~5-7 km). During June 2008-August 2008, the phase lines with altitude in the upper troposphere are almost steady (constant) indicating the source in this region. However, the phase lines are found to extending even below the tropopause to the upper troposphere during December 2007-May 2008 which may indicate that source lie few kilometers below the tropopause. Note that there are some discontinuities in the phase lines at ~20 km during MAM07, at ~17 km during SON07, at ~25 km during DJF08 and JJA08. At and above these discontinuities the phase lines appear as standing or tilted westward. From Figure 7.12 it
is quite interesting to see that the phase lines are connected as continuous propagation from one season to other season.

![Image of phase lines connecting seasons](image)

**Figure 7.12:** Same as Figure 7.11 but show Phase section.

The amplitude and phase propagation of the short period Kelvin wave (T2~ 10-12 day) of wave number 1 are shown in Figure 7.13. The amplitude shows similar structure as observed in Figure 7.11. The phase lines of the faster Kelvin waves are extended to higher altitudes above tropopause with longer vertical wavelengths in comparison to the higher period Kelvin waves. The tilting angle of the phase lines with altitude is less for short period Kelvin wave compared to higher period Kelvin waves. The amplitude and phase propagation of the wave number 2 for the period of 15 days during DJF07 and DJF08 and for period 18 days during JJA07 and JJA08 are shown in Figure 7.14. As mentioned earlier the wave number 2 is confined to the altitude region ~ 15-20 km, near the tropical tropopause. From Figure 7.14 (a) it is clear that the amplitude structures show eastward tilt with altitude.
7.3.4. Modulation of the Tropical Tropopause

The tropopause is warmer and lower during NH summer while colder and higher and NH winter, respectively. However, the day to day grided tropopause altitude and temperature in different seasons show that their variability is not always in out of phase.
Figure 7.14: Height - longitude section of the (a) amplitude and (b) phase for wave number 2 and period 15-18 days during different seasons.

Figure 7.15: Same as Figure 7.14 but for wave number 3.
Figure 7.16: The tropopause (a) altitude, and (b) temperature anomalies observed during different seasons.
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The correlation between the grided cold point tropopause altitude and temperature in different seasons is calculated. The correlation coefficient for different seasons namely SON06, DJF07, MAM07, JJA07, SON07, DJF08, MAM08 and JJA08 are (-0.25), (-0.26), -0.06, (-0.22), (-0.48), -0.12, -0.10, and (-0.46), respectively. The correlations estimated at 95% confidence level are shown in the brackets.

![Figure 7.17](image)

Figure 7.17: (a) - (d) is the amplitude of CPT temperature and (e)- (h) amplitude of CPT altitude. (i) and (j) are the corresponding phases of CPT temperature and altitude, respectively, of wave number 1 observed during different seasons for the periods 18-23 days (listed in Table1).
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Figure 7.18: Same as Figure 7.17 but for the period 9-15 day (listed in Table1).

The cold point tropopause altitudes and temperatures are well negatively correlated for the seasons SON06, DJF07, JJA07 SON07 and JJA08. Poor or no correlation is found during seasons MAM07, DJF08 and MAM08. The correlation between OLR and tropopause temperature is also estimated. It is interesting to see the positive correlation between OLR and tropopause temperature only during DJF08 (0.34) and MAM08 (0.33) for which the correlation between tropopause altitude and temperature was poor. Note that the tropopause altitude and OLR are not found to be correlated. The tropopause temperature and altitude anomalies are shown in Figure 7.16.
The dominance of the waves with various scales can be clearly seen from the Figure 7.16. As mentioned earlier, note that the tropopause altitudes show the fluctuations in wave number 1 to 4 (see Figure 7.5). Spectral analysis for the tropopause altitude and temperature is carried out during different seasons.

The dominant wave periods during different seasons are listed in the Table 7.2. Figure 7.17 (a)-(h) shows the amplitude and Figure 7.17 (i)-(j) shows phase plots of the wave number 1 component for cold point tropopause temperature and altitude for the periods (18-23 days) listed (in bold) in Table 7.2. The amplitudes of the tropopause temperature and altitude show two maxima separated by 180° in longitude. The tropopause altitude and temperature are modulated with same wave period in the range of 18-23 days. The phase diagram of tropopause altitude and temperature clearly show eastward traveling Kelvin waves during all the seasons except SON07. The phase of both tropopause altitude and tropopause temperature show westward propagation (Rossby waves) during SON07. Similarly, the phase of tropopause altitude and temperature for the period 9-15 days of wave number 1 shows eastward propagation which is clear from Figure 7.18.

Table 7.2: The dominant periodicity of the cold point tropopause temperature and altitude for wave numbers 1 to 4 during different seasons.

<table>
<thead>
<tr>
<th>Season</th>
<th>k=1</th>
<th>k=2</th>
<th>k=3</th>
<th>k=4</th>
</tr>
</thead>
<tbody>
<tr>
<td>SON06</td>
<td>10,18</td>
<td>12,18</td>
<td>6.5,9</td>
<td>7.5,10</td>
</tr>
<tr>
<td>DJF07</td>
<td>10,18</td>
<td>12,18</td>
<td>7,9</td>
<td>7.5,13</td>
</tr>
<tr>
<td>MAM07</td>
<td>9,23</td>
<td>15,23</td>
<td>6.5,10</td>
<td>7.,13</td>
</tr>
<tr>
<td>JJA07</td>
<td>12,23</td>
<td>15,23</td>
<td>6.5,10</td>
<td>6,9</td>
</tr>
<tr>
<td>SON07</td>
<td>13,23</td>
<td>12,23</td>
<td>7.5,10</td>
<td>6.5,10</td>
</tr>
<tr>
<td>DJF08</td>
<td>15,18</td>
<td>9,18</td>
<td>7.5,10</td>
<td>7,9</td>
</tr>
<tr>
<td>MAM08</td>
<td>10,23</td>
<td>15,23</td>
<td>6.5,10</td>
<td>7,13</td>
</tr>
<tr>
<td>JJA08</td>
<td>13,18</td>
<td>12,18</td>
<td>7.5,11</td>
<td>7.5,</td>
</tr>
</tbody>
</table>
Figure 7.19: The phase diagrams of tropopause temperature (left panels) and altitude (right panels) for period 6-7.5d and 9-13d for wave number 2-4 during different seasons.
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Modulation of the Tropical Tropopause

Note that the amplitudes of different periodicities of the wave number 1 are in the range of 0.1 to 0.7 K for CPT temperature and 0.02 to 0.08 km for CPT altitude. Similar spectral analysis is carried out for wave number 2, 3 and 4. The dominant periods are listed in Table 7.2. The phase diagrams for tropopause temperature and tropopause altitude for period 6-7.5d and 9-13d of wave number 2-4 during different seasons are shown in Figure 7.19. The evidence of modulation the tropical tropopause by both Kelvin wave and Rossby waves can be noticed. For wave number 2 and period 6-7.5d, tropopause temperature is modulated by Kelvin wave during all the seasons except during SON06 and SON07 which is seen modulated by Rossby waves as can be inferred from the phase propagation (Figures 7.7 and 7.18).

The tropopause altitude is modulated by Kelvin waves during SON06, DJF07, MAM07, SON07 and MAM08 while during JJA07 and JJA08 Rossby wave dominates. For wave number 2 and periods 9-13d, both tropopause altitude and temperature are found modulated by Kelvin waves. For wave number 3 and period 6-7.5d, tropopause temperature is modulated by Kelvin wave during SON06, DJF07 and JJA07 while the rest of the seasons show dominance of Rossby wave. The tropopause altitude is found modulated by Kelvin wave during MAM07, JJA07 and DJF08 and rest of the seasons by Rossby wave. During DJF07, DJF08 and JJA07, JJA08, the period 9-13d is manifestation of Kevin wave and during rest of the seasons by Rossby wave.

For wave number 4 and period 6d -7.5d, tropopause temperature is modulated by Kelvin wave during DJF06 and JJA07 while rest of the seasons show dominance of Rossby wave. The tropopause altitude is modulated by Kelvin wave during MAM07, JJA07 and DJF08 and rest of the seasons by Rossby wave. During DJF07, MAM07 and DJF08, the period 9-13d are modulated by Kevin wave and rest of the seasons by Rossby wave. For period 9-13 day, only MAM08 shows Rossby waves and rest by Kelvin wave while tropopause altitude is modulated by Kelvin wave during DJF08 and JJA08 and rest show dominance of Kelvin wave.
7.4. Summary

By taking advantage of dense number of occultations from six satellite COSMIC GPS RO measurements, the modulation of tropical tropopause by the equatorial Kelvin and Rossby waves has been investigated. The main findings are summarized below:

1) Both ground based observations from Singapore and Gadanki show similar temperature anomalies as that observed by COSMIC GPS RO measurements providing strong support to use GPS RO data for studying the equatorial waves.

2) Modulation of tropical tropopause by the equatorial Kelvin wave and Rossby waves is clearly noticed. The waves with zonal wave number up to 4 are found significant in modulating the tropopause.

3) Although period remains same, it is seen that the vertical wavelength is shorter during westerly phase of the QBO (~3-6 km) in comparison to easterly phase of the QBO (~5-7 km).

4) Kelvin waves with periodicity less than 9 days do not exist in the wave number 1 spectrum.

5) The waves with period ~5-20 days are confined to the region ~15-20 km with dominant wave numbers 2-4.

6) The cold point tropopause altitudes and temperatures are well negatively correlated but not in all the seasons.

7) No correlation is found between the tropopause altitude and OLR. Interestingly, the positive correlation between OLR and tropopause temperatures are noticed for which the correlation between tropopause altitude and temperature was poor.

Thus detailed investigation of the tropical tropopause is carried out with possible source of data and techniques whose results are summarized in next Chapter 8.