4 GRAVITY WAVE MOMENTUM FLUXES AND QUASI BIENNIAL OSCILLATION

4.1 Introduction

Quasi-Biennial Oscillation (QBO) is a classical example of the wave mean-flow interaction in the equatorial middle atmosphere. The existence of such long period oscillations came into light by the two independent pioneering works of Reed [1961]. They reported that the alternate bands of easterly and westerly winds appear at regular intervals of every two years. Further studies with longer data base reported that the period of oscillation was not biennial but varied from 24 to 30 months and hence coined the name ‘Quasi-Biennial Oscillation’ [Veryard and Ebdon, 1961; Angell and Korshover, 1964]. Subsequent observational as well as theoretical and modeling studies substantiated the characteristics of QBO in the zonal wind and temperature [Wallace, 1973; Hamilton, 1981; Lindzen and Holton, 1968; Holton and Lindzen, 1972; Plumb and Bell, 1982a, b; Plumb, 1984; Plumb and Mahlman, 1987; Dunkerton, 1997; Takahashi, 1987, 1999; Takahashi and Boville, 1992; Alexander and Holton, 1997; Mengel et al., 1995; Mayr et al., 1997; Horinouchi et al., 2003]. Much of the knowledge about the QBO has come from analysis of operational balloon-borne radiosonde observations upto 30 km and rocketsonde measurements above 30 km. Since the discovery of QBO, it has been a subject of vast interest for many decades owing to its myriad effects on the middle atmospheric circulation. A recent seminal work has extensively reviewed the characteristics of QBO and the related dynamics in the middle atmospheric region [see Baldwin et al., 2001, and references therein].

Belmont and Dartt [1968] showed that a measurement over a single station was sufficient enough to delineate the characteristics of QBO owing to its longitudinal symmetry. The salient features of this observed oscillation are: easterly and westerly wind regimes alternate regularly with a varying period of 24 to 30 months.
Successive regimes first appear above 30 km, but propagate downward at a rate of 1 km/month without loss of amplitude between 30 and 23 km, but with a rapid attenuation below 23 km. More regular and rapid descent of westerly shear zones than the easterly shear zones, long lasting westerly winds than easterly winds at higher levels while the converse at lower levels are the other prominent characteristics of QBO. Figure 4.1 illustrates the time height section of zonal wind fluctuations in the 0-40 km height region over Trivandrum with aforementioned characteristics of QBO. The latitudinal structure of the QBO amplitude exhibits a Gaussian distribution about the equator with latitudinal half width of about 12° and phase dependence on latitude within the tropics [Wallace, 1973]. Though QBO is biennial, Dunkerton, [1990] depicted that there is significant seasonal preference in the phase reversal of the onset of the easterly and westerly wind regimes. Moreover, earlier studies showed that the height of occurrence of the QBO easterly and westerly maxima varies from year to year [Reddy et al., 1986]. An interesting feature regarding the height of occurrence of the QBO maxima is that the successive maxima occur progressively at greater heights and after reaching a particular height, the maximum reappears in the lower height. Sasi [1994b] explicated this aspect extensively using 20 years of M100 rocket data over Trivandrum. He revealed that an exciting correlation exists between the height of occurrence of QBO maxima and the phenomena of the equatorial Pacific Ocean, namely the “El-Niño”. He reported that the occurrence of QBO maxima is at lower heights during or immediately after the El-Niño event and ascends to higher heights until the occurrence of next El-Niño event.

It is now well known that the tropical temperature is in thermal wind balance with vertical shear of the zonal winds [Andrews et al., 1987]. Beyond doubt, QBO exhibits a very clear signature in the temperature also. The time-height section of the temperature in the 0-40 km height region over Trivandrum exhibiting QBO is shown in figure 4.2. It can be seen from figures 4.1 and 4.2 that the occurrence of the warm/cold maxima is seen just below the easterly/westerly wind maxima. The two dimensional model of the QBO developed by Plumb and Bell [1982b] showed that warm phase of the temperature QBO occurs just below the westerly maxima and cold phase below easterly maxima. The upward progression of the warm/cold maxima corresponding to the upward
progression of the westerly/easterly maxima is also evident from figures 4.1 and 4.2. The equatorial temperature anomalies associated with QBO are of the order of ±4 K.

![Mean monthly zonal wind anomaly over Thumba (1970-2005)](image)

Figure 4.1 *Time-height section of monthly mean zonal wind anomaly during the year 1970-2005.*

The equatorial temperature anomalies associated with QBO are of the order of ±4 K. The QBO temperature variations descend down to tropopause and reach a value of the order of ±0.5 K. Studies also showed that the QBO temperature anomalies could extend up to middle and upper stratosphere and found to be out of phase with the lower stratospheric anomalies [Angell and Korshover, 1964].
Although QBO is a tropical lower stratospheric phenomenon, it highly influences the dynamics and energetics of the tropospheric and mesospheric regions, extra-tropical dynamics and transport of chemical constituents. QBO influences the tropical troposphere in many ways. Studies reported that there is a tropospheric QBO which is irregular in time, asymmetric in longitude and propagates slowly towards eastward unlike stratospheric QBO [Moron et al., 1995]. Studies on tropospheric QBO claimed that it is coherent with stratospheric QBO (SQBO) [Yasunari, 1989] while few other [Xu, 1992] disproved the same. It is also well established that the QBO play a major role in the stratosphere-troposphere exchange by modulating the upward transport of tropospheric air carrying water vapor and other tracers to the tropical stratosphere [Giorgetta and Bengtsson, 1999]. Hamilton and Garcia [1984] reported a QBO like modulation of semidiurnal surface pressure fluctuations. The tropical deep convection, which is prime source for the various waves, is found to have correlation with QBO [Collimore et al., 2003]. The QBO and Brewer-Dobson circulations modify the
constituent distributions in the tropical stratosphere. The QBO is clearly observed in tropical ozonesonde observations [Logan et al., 2003 and references therein] as well as satellite aerosol observations [Trepte and Hitchman, 1992; Grant et al., 1996] and satellite trace gas observations [Randel and Wu, 1996; Schoeberl et al., 1997; Randel et al., 1998]. The ozone QBO has been previously identified in the column measurements [Bowman, 1989; Hollandsworth et al., 1995; Randel and Wu, 1996] and in profile measurements from Stratospheric Aerosol and Gas Experiment II (SAGE II) observations [Zawodny and McCormick, 1991; Randel and Wu, 1996], HALOE observations [Dunkerton, 2001] and ozonesonde observations [Logan et al., 2003]. Thus, QBO signature has Omni-presence in the Earth’s atmosphere, which is confirmed by various observational platforms.

Further, QBO controls the dynamics and energetics of the mesospheric region by the selective filtering of the vertically propagating waves of various scales. Besides the tropospheric QBO, HRDI measurements onboard UARS satellite along with MF radar observations at Christmas Island revealed a QBO in the mesospheric region (MQBO) [Burrage et al., 1996]. This study reported that MQBO is out of phase with SQBO while the latitudinal extent is same as that of SQBO. Study by Jarvis [1997] showed that QBO modulates the semidiurnal tide which propagates from troposphere to lower thermospheric regions. The semidiurnal tide appeared to propagate upward more easily during the easterly phase of the tropical stratospheric QBO than during the westerly phase. Both theoretical and observational studies showed that the QBO in the zonal wind can affect the tidal oscillation in the MLT region [Gurubaran and Rajaram, 1999; Hagan, 1999]. Vincent et al., [1998] suggested that the inter-annual variability in the MLT region is linked to the phase of equatorial QBO. Modulation of MSAO by the lower stratospheric winds has been illustrated by observational as well as modeling studies [Burrage et al., 1996; Garcia and Sassi, 1999]. Apart from influencing the neutral atmospheric dynamics, this longer period oscillation in the lower stratospheric region impinges its signature in the ionospheric region also. QBO is believed to affect the strength and day to day variability of the equatorial ionospheric phenomena, namely the Equatorial Ionization Anomaly (EIA) by the selective filtering of planetary waves [Chen, 1993] and Counter Electrojet (CEJ) events [Chen et al., 1995]. Geomagnetic field
variations which are due to dynamo action of the thermospheric winds and the
ionospheric conductivity are found to have high correlation with the lower stratospheric
QBO [Olsen, 1994]. Studies also reported the relation between solar UV irradiance and
easterly and westerly phases of QBO [Elias et al., 2003].

Apart from zonal wind and temperature, QBO signals are manifested in
other meteorological parameters also. These variables either affect or are being affected
by the QBO. There are more number of observational studies on the relation between the
QBO, El-Nino and La-Nina events [Yasunari, 1989; Xu, 1992; Angell, 1992]. Maruyama
and Tsuneoka [1988] reported that ENSO warm events enhance the rate of QBO westerly
Stratospheric QBO acts as one of the potential predictors of the Atlantic hurricane
activity [Gray, 1984; Landsea et al., 1998; Elsner et al., 1999] while its role in the
typhoons in the western Pacific region is unclear [Lander and Guard, 1998] owing to the
different mechanisms involved in these major catastrophes of the life. QBO can influence
the rainfall activity [Mohankumar, 1989] and precipitation regimes [Fontaine et al.,
1995] of the tropical regions. It is seen that Sea Surface Temperature (SST) is modulated
by the QBO along with solar activity [Trenberth, 1975; Mason and Tyson, 1992]

Notwithstanding the fact that QBO is confined to tropical latitudes, its
effects are obvious in the middle and high latitudes too. The influence of QBO in the
extratropical middle atmosphere is more prominent during the northern hemisphere
winter. Holton and Tan [1980] gave an evidence for the QBO modulation of the mean
zonal winds and planetary waves of the geopotential field of the high latitude
stratosphere. Corroborating their results Labitzke [1982] and vanLoon and Labitzke
[1987] pointed out that the stratospheric polar vortex in the northern winter is stronger
and arctic middle stratosphere tends to be colder during the easterly phase of the QBO
than during the westerly phase. Sudden stratospheric warmings (SSW) are the most
exciting events that take place in the polar stratosphere during winter. Studies revealed
that the QBO acts as one of the governing factors in the occurrence of the SSW. An
interesting result documented by Labitzke [1982], in this regard, is that more major
stratospheric warmings occur in the easterly phase of the QBO. She also elucidated
possible correlations between QBO, sunspots and the stratospheric temperatures in the northern polar winter [Labitzke, 1987]. There is suggestion of a feedback loop between the modulation of extratropical temperature by the QBO, the formation of polar stratospheric clouds and hence with the underlying chemical destruction that gives rise to the ozone hole [Butchart and Austin, 1996]. From the above discussion it is quite evident that apart from insolation, QBO controls the dynamics of the middle and upper atmosphere of the equatorial as well as middle and high latitudes.

4.1.1 Forcing Mechanisms of QBO

Beyond that envisaged in the 1960’s, as discussed above, QBO has an insurmountable role in the global circulation, dynamics, chemistry and climate. However, the mechanisms involved in the origin, dynamics and structure of this intriguing mystery still remains an enigma to the middle atmospheric researchers. Various theories and models have been put forth in order to explain the salient characteristics of the QBO such as 1) its biennial periodicity, 2) zonally symmetric winds at the equator and 3) vertical descent of westerly and easterly shear zones without the loss of amplitude. During the initial phase of the discovery of the QBO, two mechanisms were believed to be responsible for the observed features of QBO, one was the diabatic heating and other, the horizontal eddy momentum flux divergence. In an attempt to simulate the QBO based on the above said mechanisms, Wallace and Holton [1968] ruled out both of them owing to their inability to reproduce the amplitude and the downward descent of the observed oscillation. They gave a suggestion that the momentum source should also propagate downward to account for the observed downward acceleration. However, none of the earlier theoretical simulations and modeling studies explained the most conspicuous features of QBO.

Deposition of the momentum fluxes due to radiative damping and critical level filtering by waves of various scales is believed to be responsible for the generation of the QBO. In an interesting seminal work, Lindzen and Holton [1968] proposed that interaction of a long period vertically propagating gravity waves with zonal wind could drive the QBO in the tropical lower stratosphere. Their idea is based on the novel work of Booker and Bretherton’s [1967] on the critical level absorption of gravity waves.
Unfortunately, there was no observational evidence of atmospheric waves to concur their results. Though many theories have been proposed to explain the features of the QBO, modeling work by Holton and Lindzen [1972] gave conceptual idea of the generation of the QBO based on Lindzen and Holton model [1968]. According to their study, wave momentum necessary to drive the westerly/easterly phases of the QBO are imparted primarily by vertically propagating large-scale equatorial Kelvin [Wallace and Kousky, 1968a, b] and Rossby-gravity waves [Yanai and Maruyama, 1966]. The interaction of these waves with mean flow leads to acceleration of the mean flow. Plumb [1977] showed that the QBO period decreases with increase in wave momentum fluxes. Dunkerton [1981] in his numerical simulation of the QBO found that, when the wave flux due to RG wave was reduced by a factor of 2, the QBO period increased by 22%. Similarly the changes in Kelvin wave flux also could alter the lengths of the westerly and easterly phases of the QBO. Even though it is established that the equatorial wave momentum fluxes could significantly alter the characteristics of QBO, further observational and modeling studies showed that the observed amplitudes of these two wave modes are too weak to account for the downward acceleration of QBO [Gray and Pyle, 1989; Takahashi and Boville, 1992; Kinnersly and Pawson, 1996; Sato and Dunkerton, 1997]. The deficit in the momentum flux predicted by these authors became more evident after the study by Dunkerton [1991] who showed that equatorial wave fluxes are meager in the presence of tropical upwelling. All these studies unanimously suggested that an amplitude increase by a factor of two is needed to achieve a realistic QBO.

Over the present observational site, Gadanki, Sasi and Deepa [2001] estimated the equatorial wave momentum fluxes during different seasons in the lower atmosphere from winds measured by Indian MST radar, using a method developed by Sasi et al., [1999]. Using the horizontal flux divergence of the observed momentum flux values at the tropopause height, mean flow acceleration was simulated up to 30 km height in the stratosphere. Meanflow accelerations in the zonal winds measured from balloon flights over Trivandrum during 1995-1996 were calculated in the 17-30 km height region and compared with simulated ones obtained using the momentum flux divergence (MST radar) for different seasons. These mean-flow accelerations during equinoxes and
solstices are shown in figures 4.3 and 4.4 respectively. The horizontal bar denotes the r.m.s. deviations of the acceleration at different levels. It is seen from figure 4.3 that the observed and simulated accelerations during vernal equinoxes are agreeing with each other in 17-25 km height region. Above 25 km, the observed and simulated accelerations are in exactly opposite direction. In the case of autumnal equinox there appeared to be a large deviation of the simulated acceleration from the observed one below 28 km height region.

Similarly there existed a large discrepancy between the observed and simulated meanflow acceleration above 25 km and between 20 and 25 km during winter and summer seasons also (figure 4.4). Though the simulated and observed meanflow acceleration at stratospheric levels were, in general, agree with each other, in certain

![Graph showing simulation and observation of mean flow acceleration in the stratosphere.](image)

**Figure 4.3** Height profile of mean flow acceleration in the stratosphere. Continuous line represents simulated values and filled circles represent observed values from balloon data. (a) Autumnal equinox (b) Vernal equinox. Horizontal bars in the observed values show the dispersion. [After Sasi and Deepa, 2001].

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height regions significant differences between the two were observed. All these studies suggested that an additional wave momentum is necessary to drive the QBO.

Figure 4.4. Height profile of mean flow acceleration in the stratosphere. Continuous line represents simulated values and filled circles represent observed values from balloon data. (a) Winter (b) Summer. Horizontal bars in the observed values show the dispersion. [After Sasi and Deepa, 2001].

In the light of the existing theories, Dunkerton [1997] emphatically showed that the additional forcing needed to drive the QBO could be provided by the small scale internal gravity waves. Subsequent modeling [Mengel et al., 1995; Alexander and Holton, 1997; Mayr et al., 1997, 1999; Piani et al., 2000; Scaife et al., 2002; Alexander and Vincent, 2000; Horinouchi et al., 2003] as well as observational studies [Pfister et al., 1993; Sato and Dunkerton, 1997; Vincent and Alexander, 2000; Hertzog and Vial, 2001] also accentuated the role of gravity waves in driving the QBO. However, modeling studies could only fairly reproduce these long period oscillations, since the gravity wave characteristics such as source mechanisms and propagation characteristics exhibit a wide range of variability in both spatial and temporal scales. Thus, the
knowledge of the momentum spectrum of these waves is crucial in redefining the input parameters to general circulation models. In a seminal work, McLandress [1998] discussed the importance of gravity waves on the general circulation of the middle atmosphere and also described different ways of parameterizing their effects on the global atmospheric models. Nevertheless, quantifying the role of these waves still remains illusive until a more complete knowledge is attained of momentum spectrum of these waves.

4.1.2 Gravity Wave Momentum Fluxes in the Tropospheric Region

Though several studies explicated the gravity wave activity in the lower stratosphere, very few addressed the gravity wave momentum fluxes as such and their forcing towards the generation of QBO. Different platforms have been employed to measure the gravity wave momentum fluxes in the tropospheric region which includes aircrafts, radiosondes, VHF radars as well as satellites. With advent of aircraft measurements, in-situ measurements of gravity wave momentum fluxes have been carried out without making any ad-hoc assumptions about the wave parameters and their sources. Studies made use of winds and temperatures from aircraft measurements to estimate the momentum fluxes of gravity waves generated by topography [Nastrom and Fritts, 1992]. Pfister et al., [1993] described the potential of using aircraft measurements for observing mesoscale gravity waves and estimated the momentum fluxes of gravity waves of horizontal wavelengths ~100 km and periods of a few hours over tropical convective systems. Alexander and Pfister [1995] estimated the momentum fluxes of gravity waves of horizontal scales ≤ 100 km above deep convection during Stratosphere-Troposphere Exchange (STEP) project and showed that the gravity waves propagate away from the convection which was in very good agreement with earlier modeling studies by Alexander et al., [1995]. Lilly et al., [1992] reported the gravity wave momentum fluxes over Rocky Mountains at Colorado using aircraft measurements.

Balloon- borne radiosonde measurements have also been extensively used to estimate the gravity wave momentum fluxes in the tropospheric-lower stratospheric regions. Initially, the quadrature spectra of the zonal wind and temperature fluctuations derived using radiosonde observations were used to estimate the momentum fluxes of
both equatorial waves and gravity waves in the tropospheric region [Mauryama, 1991, 1994]. Later, Sato et al., [1994] reported that the co-spectra of the zonal wind and temperature fluctuations are in perfect synchronization with the background wind shear (i.e., the vertical flux changes its direction in accord with the mean background wind) which is hardly found in the momentum fluxes estimated by the quadrature spectra. Subsequent numerical as well as theoretical studies by Dunkerton [1995, 1997] briefly explained the Sato’s findings for slowly varying gravity waves. Sato and Dunkerton [1997] proposed an indirect method to estimate the gravity wave momentum fluxes from the cross spectra of zonal wind and temperature fluctuations at Singapore (1.4°N, 104.0°E) and quantitatively evaluated the Dunkerton’s theory. Their method is particularly important for short period gravity waves that can propagate in all directions. They showed that momentum flux estimated from the co spectra gives the summation of absolute values of momentum flux associated with each wave whereas that estimated from quadrature spectra gives the summation of momentum flux. Studies using continuous six years of high resolution radiosonde observations over Cocos Islands in the Indian ocean could estimate the upward flux of horizontal momentum of inertia gravity waves and the observed wave characteristics were elaborated using linear model [Vincent and Alexander, 2000; Alexander and Vincent 2000].

There are studies on gravity wave momentum fluxes using VHF radars in the lower atmosphere. Dual beam radar method proposed by Vincent and Reid [1983] has been widely used to estimate the gravity wave momentum fluxes all over the globe which includes MU radar at Shigaraki, [Sato, 1990, 1994; Fritts et al., 1990; Murayama et al., 1994], MST radat at Aberystwyth, Wales (52°N, 4°W) [Prichard and Thomas, 1993; Worthington and Thomas, 1997], ST radar at Christmas Isalnd (1.95°N, 157.30°W) [Chang et al., 1997], MST radar at Jicamarca, (12°S, 77°W) [Riggin et al., 1997, 2004], EAR radar at Indonesia (0.2°S,100.32°E) [Alexander et al., 2008] while several other studies were devoted to delineate the errors involved in the estimation of gravity wave momentum fluxes [McAfee et al., 1989; Kudeki and Franke, 1998; Thorsen et al., 2000; Riggin et al., 2004; Dutta et al., 2005, 2007]. Over the present observational site, Gadanki, Dutta et al., [2005] and Reddy et al., [2005] estimated the gravity wave
momentum fluxes in the tropospheric region using Indian MST radar. Apart from ground based observations, Satellites observations were also made to elucidate the global picture of the gravity wave momentum fluxes [Ern et al., 2004].

Routine measurements of gravity wave momentum fluxes in the lower stratospheric region are, however, very sparse. Most of these observations are limited either in space or in time. In this regard, Rayleigh lidar is proved to be quite powerful in providing routine measurements of high-resolution density and temperature fluctuations in the 27-60 km altitude region. A series of experiments were conducted at the present observational site, Gadanki, using radar and lidar observations [Dutta et al., 1999; Dhaka et al., 2002; Kumar, 2006, 2007a; Sivakumar et al., 2003, 2006; Rajeev et al., 2003; Deepa et al., 2006a]. Using lidar observations, detailed studies were carried out on middle atmospheric thermal structure and gravity wave characteristics such as their growth, saturation and associated potential energy over Gadanki [Sivakumar et al., 2003, 2006]. However, none of these studies focused on quantifying the role of gravity waves in driving both easterly and westerly phases of QBO. Even such studies are very limited across the globe.

The difficulty in the measurement of gravity wave momentum fluxes in the stratospheric region involves the determination of wind components with good accuracy. Without the knowledge of both horizontal and vertical winds, Krishna Murthy et al., [2002] using a novel approach estimated the momentum fluxes of equatorial Kelvin waves from temperature fluctuations. Later Deepa et al., [2006a] estimated the momentum fluxes of gravity waves using the same method over the present observational site but with a limited data set. This method makes use of gravity wave polarization relation which inter relates the three components of winds and temperature fluctuations. The central objective of present work is to estimate the gravity wave momentum fluxes and to elucidate its seasonal variation in the 30-60 km altitude region using the lidar derived temperature fluctuations over seven years (1998-2005) which includes data under MIDAS program also. An attempt is also made to quantify the role of gravity waves in the generation of westerly and easterly phases of the QBO in the lower stratospheric region (27-32 km). The monthly mean zonal winds from NCEP/NCAR reanalysis data
over Gadanki are also used to study the characteristics of QBO and the mean flow acceleration.

4.1.3 Method for Estimation of Gravity Wave Momentum Fluxes from the Polarization Relations

The vertical flux density of horizontal momentum is a two-dimensional vector quantity that describes the direction of the horizontal momentum that is being advected vertically and the rate at which it is being advected. In general, the components of this vector are denoted $\rho u'w'$ and $\rho v'w'$ where $\rho$ is the density; the over bar denotes temporal averaging. The total wind velocity vector can be represented by $U = \overline{U} + U'$ where $U' = (U', V', W')$ is the instantaneous perturbation about that mean. The time average that is inherent in this linearization process has the effect of excluding contributions due to periodic variations with timescales that are significantly longer than averaging interval. These longer-term variations contribute to the mean in successive averaging intervals but are not represented in the perturbation quantities. Thus the linearization process partitions the velocity variations by frequency such that higher-frequency components (from the Nyquist frequency down to approximately the inverse of the sampling interval) are present in the time series of the perturbation velocity vector $U'$, while lower frequency components remain in $\overline{U}$. In turn, the vertical flux density of horizontal momentum described by $\rho u'w'$ and $\rho v'w'$ is due to velocity variations whose frequencies are similarly defined by the averaging interval and the linearization process. The momentum flux densities of two waves of the same frequency can be summed if the waves are independent of each other. The vertical flux of horizontal momentum can be estimated from the zonal ($u$), meridional ($v$) and vertical ($w$) winds measured using ground based VHF and MF radars in the tropospheric and mesospheric region.

For a compressible and inviscid atmosphere ignoring the gradients in the background flow $u$ by setting $(u_0, v_0, 0)$, the linearised momentum, continuity equation and ideal gas equations become [Andrews et al., 1987]
\[
\frac{Du'}{Dt} - f\nu' = -\frac{1}{\rho_0} \frac{\partial p'}{\partial x'} \tag{4.1}
\]
\[
\frac{Dv'}{Dt} + fu = -\frac{1}{\rho_0} \frac{\partial p'}{\partial y'} \tag{4.2}
\]
\[
\frac{Dw'}{Dt} = -\frac{1}{\rho_0} \frac{\partial p'}{\partial z'} \frac{\rho'}{\nu_0} \tag{4.3}
\]
\[
\frac{Dp'}{Dt} + w' \frac{\partial p_0}{\partial z} + \rho_0 \nabla \cdot u' = 0 \tag{4.4}
\]
\[
\frac{Dp'}{Dt} + w' \frac{\partial p_0}{\partial z} + c_s^2 \left( \frac{d\rho'}{dt} + w' \frac{\partial \rho_0}{\partial z} \right) = 0 \tag{4.5}
\]

Here \( \frac{D}{Dt} = \frac{\partial}{\partial t} + u \nabla \) is the total (Lagrangian) derivative and \( u' = (u', v', w') \), \( p' \) and \( \rho' \) are the perturbation velocities, pressure and density, respectively. \( p_0 \) and \( \rho_0 \) designate the background pressure and density, respectively; which are assumed to vary only with height; \( f \) is the coriolis parameter, \( g \) is the acceleration due to gravity and \( c_s \) is the speed of the sound.

Substituting solutions of the form

\[
\begin{pmatrix} u' \\ v' \\ w' \\ p' \\ \rho' \end{pmatrix} = \rho_0^{-\frac{k}{2}} \begin{pmatrix} \hat{u} \\ \hat{v} \\ \hat{w} \\ \hat{p} \\ \hat{\rho} \end{pmatrix} \exp(i(kx-\omega t)) \tag{4.6}
\]

where \( k = (k, l, m) \) and \( x=(x, y, z) \), and expressing the intrinsic frequency in a reference frame following the background flow as

\[
\hat{\omega} = \omega - ku \tag{4.8}
\]

yields the non hydrostatic dispersion relation that relates the wave frequency to the wave's spatial characteristics (wave numbers) and background atmospheric properties \( N \).
\[ m^2 = \frac{N^2 - \omega^2}{\omega^2 - f^2} \left( k^2 + l^2 \right) - \frac{1}{4H_p^2} + \frac{\hat{\omega}^2}{c_i^2} \]  

(4.9)

where

\[ N^2 = -\frac{g}{\rho_0} \frac{\partial \rho}{\partial z} \frac{g^2}{c_s^2} \]  

(4.10)

is the buoyancy or Brunt-Väisälä frequency and

\[ H_p = \frac{1}{\rho_0} \frac{\partial \rho_0}{\partial z} \]  

(4.11)

the density scale height. The dispersion relation (4.9) also includes an acoustic branch. For an incompressible atmosphere, acoustic waves can be excluded by letting \( c_s \to \infty \). Further the omission of the second term of equation (4.9) results in the Boussinesq approximation, a short wavelength approximation valid for \( m \gg 1/2H_p \).

The polarization relations are simplified in coordinate system aligned with the propagation direction of the wave. Let \( u'_1 \) and \( v'_1 \) denote the horizontal perturbation velocities parallel and perpendicular, respectively, to the wave vector. The relevant polarization equations in the Boussinesq approximation then become

\[ v'_1 = -i \frac{f}{\hat{\omega}} u'_h \]  

(4.12)

\[ w' = -\frac{k_h}{m} u'_h \]  

(4.13)

\[ \hat{T}' = \frac{T'}{T_0} = i \frac{N^2}{g \hat{\omega}} \frac{k_h}{m} u'_h \]  

(4.14)

where \( T' \) and \( T_0 \) are the perturbation and background temperature, respectively, and \( k_h \) is the horizontal wave number. From equation (4.14) it is seen that the zonal wind component is in quadrature phase with temperature and the co spectra of \( u \) and \( T \) can be used to estimate the vertical flux of zonal wind component if the temperature change is assumed to be caused by the wave-associated vertical motion as in all previous studies [Allen and Vincent, 1995; Vincent and Alexander, 2000; Sato and Dunkerton, 1997].
Substituting equation (4.13) into equation (4.1) and rearranging, we get the vertical flux of zonal momentum per unit density. The vertical flux of the zonal momentum per unit density \( F \) of gravity waves can be estimated using the following equation:

\[
F = \langle u'w' \rangle = \frac{k}{m} \left( \frac{g}{N} \right)^2 \left( \frac{T'}{T} \right)^2 \approx \frac{\omega}{N} \left( \frac{g}{N} \right)^2 \left( \frac{T'}{T} \right)^2
\]  

(4.15)

Here the assumption made is \( N \gg \omega \gg f \), where \( \omega \) is frequency of the gravity wave and \( f \) is the Coriolis parameter. In equation (4.15), the last term only is used to estimate the gravity wave momentum flux which does not contain vertical wave number. Also in equation (4.15), though the wave characteristics such as frequency and vertical wave number are assumed to be constant, the altitude variations in the temperature perturbations due to gravity waves will lead to variations in the momentum fluxes with height. Here it is to be noted that the gravity wave is resolved into zonal and meridional components and the above equation gives the zonal momentum flux. As the time variations of the temperature can be obtained with continuous lidar data, this analysis proves better than earlier studies of momentum flux estimates by applying the same technique to a single profile without knowing a dominant wave frequency.

As discussed in Chapter 3, 2-4 hour and 0.5-1 hour band periods of gravity waves were prominently present in the data on almost all the observational days. The amplitude and phase derived using the Fourier analysis of these two bands of periods of gravity waves were reconstructed using the formula

\[
u(t) = A(t) \cos \left( 2\pi n \frac{t}{T} - \varphi(t) \right)
\]  

(4.16)

where \( \nu(t) \) is the reconstructed temperature fluctuations corresponding to the particular period of the gravity wave. \( A(t) \) and \( \varphi(t) \) is the amplitude and phase of the particular period of the gravity wave respectively. \( T \) is the period of the wave, \( n \) the sampling interval, here it is 12.5 minutes and \( t \) is instantaneous time. Thus the reconstructed temperature fluctuations corresponding to these two bands of periods of gravity waves were used to estimate the gravity wave momentum fluxes as given in equation (4.15).
The momentum flux values of 0.5-1 hour and 2-4 hour period gravity waves on all available days in a month is averaged to get the monthly mean momentum fluxes.

4.2 Database

Lidar temperature data during the MIDAS program (November 2002-April 2005, as discussed in Chapter 3) has been made use to estimate the momentum fluxes of 0.5 -1 hour and 2-4 hour band period gravity waves and their seasonal variation. In order to quantify the role of these two prominent bands of periods of gravity waves towards the forcing of easterly and westerly phases of QBO, lidar data collected during April 1998- April 2005 are used in the present study with a data gap mostly during monsoon months. During monsoon season, the lidar observations were restricted to very few hours owing to unfavorable weather conditions for lidar operation and couldn’t be used for extracting the gravity wave parameters. There are few months during which lidar observations were not available due to the maintenance of the system. With these data gaps the lidar observations of temperature profiles are extensively used for the present study during the above mentioned.

The monthly mean zonal winds averaged over 10-15°N and 75-80°E grid from the NCEP/NCAR reanalysis data are obtained from www.cdc.noaa.gov at two pressure levels, 20 and 10 hPa. These observations are used to investigate the QBO characteristics and its month-to-month acceleration. Monthly mean zonal winds in the 27-30 km altitude region obtained using HAB over Trivandrum under MIDAS program are also used in the present work. The errors in the HAB wind measurements are 1-2m/s for wind speed and for wind direction, 5 degrees for wind speeds above 25 m/s and 10 degrees for lower wind speeds.

4.3 Results and Discussion

4.3.1 Altitude variation of gravity wave momentum fluxes

Figures 4.5(a)-(d) show the altitude profiles of monthly mean momentum fluxes for the 2-4 hour band of gravity waves for four different seasons. From figures 4.5
Figure 4.5 Monthly mean altitude profiles of momentum fluxes of gravity waves of periods 2-4 hour during (a) April 2001 (b) June 2001 (c) September 2001 and (d) December 2001.
(a) and (c), it can be seen that the momentum fluxes during April 2001 range from ~0.02 to 1.5 m$^2$s$^{-2}$ while it is ~0.01 to 1.4 m$^2$s$^{-2}$ during September 2001 in the 30-60 km height region. During June 2004 the momentum fluxes of the 2-4 hour band varies from 0.01 m$^2$s$^{-2}$ to 0.9 m$^2$s$^{-2}$ (figure 4.5 b). The momentum fluxes during November 2004 are found to vary from 0.1 to 1 m$^2$s$^{-2}$ in the 30-60 km altitude region. The momentum fluxes of gravity waves during April 2001 are less than that during September 2001. During monsoon seasons owing to the cloudy sky conditions the number of available days of observations was very less, which resulted in the larger errors in the monthly mean momentum flux values during September 2001. Moreover, on some observational days the data collected could not be used for the gravity wave studies. Another interesting feature which is observed in all the months is the exponential increase in the momentum flux with height. The wave energy increases with height as the wave propagates upwards owing to the decrease in density with height. It is also evident from these figures that the wave growth is different in the stratospheric and mesospheric regions. This characteristic feature of the wave growth is similar to that observed in the potential energy of the gravity waves [refer to figures 3.7]. There is no significant variation in the momentum fluxes in the 30-40 km altitude regions in all the seasons. In the 40-60 km altitude regions, momentum flux values are maximum during April 2001 and September 2001. The momentum flux values are minimum during June 2001 and November 2001. A clear seasonal variation in the gravity wave momentum fluxes is thus evident from the figures 4.5 (a)-(d).

The altitude profiles of momentum fluxes for the 0.5-1 hour period gravity waves during four different seasons are shown in figures 4.6(a)-(d). The momentum fluxes range from ~0.03 to 3.8 m$^2$s$^{-2}$ in April 2001 while it is 0.02 to 4 m$^2$s$^{-2}$ during September 2001. During June 2001, momentum fluxes vary from 0.01 to 1.5 m$^2$s$^{-2}$. The momentum fluxes during November 2001 range from 0.02 to 2 m$^2$s$^{-2}$ as compared to all other seasons. The estimated errors in the momentum fluxes are less than 0.05 m$^2$s$^{-2}$ below 50 km for both bands of period gravity waves. Generally, the momentum fluxes of 0.5-1 hour period band is more than the 2-4 hour band. Fritts and Vincent [1987] reported that the high frequency gravity waves carry 75% of the momentum fluxes to the upper atmosphere.
Figure 4.6 Monthly mean altitude profiles of momentum flux of gravity waves of periods 0.5-1 hour during (a) April 2001 (b) June 2001 (c) September 2001 and (d) December 2001
Comparison of the inferred momentum fluxes with other techniques is difficult since such observations are very few over the globe. Moreover such studies are limited to tropospheric and mesospheric regions. Studies using MU radar (35°N, 133°E) observations reported the gravity wave momentum fluxes in the range of ~0.1-0.3 m²s⁻² in lower stratospheric region [Fritts et al., 1990]. However, the MU radar observations revealed that the momentum fluxes are generally less than 1 m²s⁻² in 60-90 km altitude region [Tsuda et al., 1990]. Zonal momentum fluxes of the order of 2-8 m²s⁻² were reported using VHF radar observations over Jicamarca (12°S, 77°W) in the 70-85 km height region [Hitchman et al., 1992]. The gravity wave momentum fluxes in the tropospheric regions were estimated to be around -0.15 to 0.25 m²s⁻² [Murayama et al., 1994]. Using rawinsonde observations over Singapore (1.4°N, 104°E), Sato and Dunkerton [1997] using cospectra of zonal wind and temperature fluctuations estimated the gravity wave momentum fluxes in the lower stratospheric region which were found to be 0.02-0.06 m²s⁻² which they termed as indirect method of measuring the momentum fluxes. The estimated momentum fluxes using the indirect method was found to be larger than that computed directly from zonal and vertical wind fluctuations and suggested that there could be significant flux cancellation due to both eastward and westward propagating waves.

The momentum fluxes of the gravity waves excited due to the topography were observed to be ~0.01 to -1.42 m²s⁻² [Nastrom and Fritts, 1992]. Studies using ST radar over Christmas Island documented that estimated momentum fluxes of waves with period shorter than 8 hours range between ±0.02 and ±0.01 kg m⁻¹s⁻² in the tropospheric region [Chang et al., 1997]. Prichard and Thomas [1993] estimated vertical flux of horizontal momentum for waves with periods less than 6 hours in the troposphere using VHF radar data located at Aberystwyth. Their zonal and meridional momentum flux estimates per unit mass ranged between ±0.01 m²s⁻². Riggin et al., [1997] found that the most of the stratospheric momentum flux were carried by the waves with periods greater than 4 hours. The estimated momentum fluxes of 4 hour period gravity waves were in the range of <0.1 m²s⁻² in the 20-30 km altitude region. The momentum fluxes of gravity waves of periods in the range 1 hour-1 day were reported to be 0.008 to 0.012 m²s⁻² at 20 km [Hertzog and Vial, 2001]. Using Indian MST radar Dutta et al., [2005] reported
that the mean momentum flux per unit mass over Gadanki, are found to vary between ±0.03 m²s⁻² and ±0.02 m²s⁻² for zonal and meridional winds, respectively. From EWS campaign, the gravity wave momentum fluxes in the altitude region 30-60 km over the present observational site were found to be in the range 0.05-0.2 m²s⁻² [Deepa et al., 2006]. The magnitude of momentum fluxes observed in the present study in the 30-60 km height region are thus consistent with those reported in the literature. From the above discussion it is clear that the studies on the gravity wave momentum fluxes in the stratospheric region (30-60 km) are very sparse in the tropical latitudes. Thereby the present study bears its importance by estimating the gravity wave momentum fluxes in the stratospheric region.

4.3.2 Seasonal Variation of Gravity Wave Momentum Fluxes

The monthly mean profiles of momentum fluxes of 2-4 hour and 0.5-1 hour period gravity waves in the 30-60 km altitude regions are multiplied with density and then block averaged in the same height region to elucidate their seasonal variations. The monthly mean profiles of density are taken from the mean tropical atmospheric model by Sasi [1994a]. Figures 4.7 show the composite annual cycle of momentum fluxes for 2-4 hour band periods of gravity waves during the observational period. It can be seen from figure 4.7 that momentum fluxes are maximum during April and August and minimum during winter (November, December, January, February) and summer (June) months for the 2-4 hour period gravity waves.

The composite annual cycle of momentum fluxes for 0.5-1 hour band periods of gravity waves is depicted in figure 4.8. The gravity waves with time periods 0.5-1 hour also show a similar seasonal variation as 2-4 hour period gravity waves as shown in figure 4.7, except the summer minima which is not as clear as in the case of 2-4 hour period gravity waves. As a whole, during the observational period, 2002-2005 both 2-4 hour and 0.5-1 hour period gravity waves show semiannual variation with maximum around equinoctial months and minimum during the solstitial months. The seasonal variation in the gravity wave momentum fluxes in the troposphere and lower stratosphere regions (5-25 km) using monthly observations of MU radar showed a clear annual variation with winter maximum and summer minimum [Murayama et al, 1994].
1. Studies on gravity waves with periods 5 min to 2 hours using the MU radar in the mesospheric regions (65-80 km) reported that the zonal fluctuations show a semiannual variation with summer maximum and irregular enhancements in winter [Tsuda et al., 1990]. From the present study it is clear that the gravity wave activity show semiannual variation with equinoctial maxima in contrast to mid latitudes, which show summer and winter maxima.
4.3.3 Estimation of Mean Flow Acceleration from Monthly Mean Zonal Winds

4.3.3.1 Comparison of NCEP with HAB over Trivandrum

As there are no direct wind measurements in the 27-32 km altitude region over Gadanki, monthly mean zonal winds from NCEP/NCAR reanalysis data during May 1997-April 2006 are used to divulge the characteristics of QBO. As a first step, monthly mean zonal winds from NCEP averaged over 5-10°N and 75-80°E grid are compared with the High Altitude Balloon (HAB) wind observations at Trivandrum (8.5°N, 76.9°E). Monthly mean zonal winds in 0-60 km altitude region using rocket soundings and HAB are available over Trivandrum during November 2002-November 2007 under MIDAS program [Ramkumar et al., 2006].

![Comparison of the monthly mean zonal winds from HAB observations (solid line) and NCEP (solid line with circle) over Trivandrum at 20hPa during November 2002-October 2006](image)

Figure 4.9 Comparison of the monthly mean zonal winds from HAB observations (solid line) and NCEP (solid line with circle) over Trivandrum at 20hPa during November 2002-October 2006

It is well known that the input to the NCEP in the 25-30 km altitude region is very sparse since radiosondes over Indian latitudes give wind information only up to 25 km and are mostly interpolated in this region. The main purpose of the present
comparison is to show the validity of the NCEP in the gap region 25-30 km region. Figures 4.9 and 4.10 show the comparison of the monthly mean zonal winds from NCEP over Trivandrum and HAB zonal winds over Trivandrum at two levels, 10 and 20 hPa respectively. From the figures it is observed that zonal winds obtained from NCEP correlates well with that of HAB. There is shift in the month of maximum zonal wind velocity as measured by NCEP and that of HAB measurements at 20 hPa (refer to figure 4.9). At 10 hPa level, both measurements are in good agreement.

Though there are some discrepancies, NCEP could capture the long-term characteristics and agrees well with the in-situ observations of zonal winds in the lower stratospheric region. An Earlier study by Krishnan et al., [2005] showed a very good agreement between the NCEP zonal winds and UHF radar measured zonal winds at lower altitudes over Gadanki (13.5°N, 79.2°E). Based on the above comparison and the comparison of the NCEP zonal winds in the lower tropospheric region with MST radar observations over Gadanki, zonal winds in the lower stratospheric region is used to study the forcing of gravity waves towards the generation of easterly and westerly phases of QBO.

![Graph showing comparison](image)

**Figure 4.10** Comparison of the monthly mean zonal winds from HAB observations (solid line) and NCEP (solid line with circle) over Trivandrum at 10 hPa respectively during November 2002-October 2006
4.3.3.2 Characteristics of QBO over Gadanki

Figure 4.11 shows the monthly mean zonal winds (averaged in the 10-15°N and 75-80°E grid) at two pressure levels, 20 hPa (dotted line) and 10 hPa (solid line), during May 1997-April 2006. Even though lidar observations are available only from April 1998-April 2005, zonal winds from May 1997-April 2006 are used in the present study in order to cover four complete cycles of QBO. The first QBO cycle is from May 1997-March 1999, second QBO cycle selected is from April 1999-March 2002, third cycle is from April 2002-April 2004 and fourth one is from May 2004-April 2006. The maxima of both the westerly and easterly phase at 20 hPa level occur at a month later than that at 10 hPa level confirming the descending of the shear zones. The easterly phase of all QBO cycles start during May while the westerly phase during October. From figure 4.11 it is seen that the easterlies are stronger with maximum of ~35 ms⁻¹ than westerly maximum of ~16 ms⁻¹, which is in accordance with the earlier studies.

![Figure 4.11](image)

**Figure 4.11** *Time series of the monthly mean zonal winds over Gadanki at 20 hPa (dotted line) and 10 hPa (solid line) during May 1997-April 2006*

Studies using balloon and rocketsondes observations over three rocket ranges in India, namely Thumba (8.5°N, 76.9°E), SHAR (13.7°N, 80.2°E), and Balasore...
(21.5°N, 86.9°E) showed that the maximum of the QBO amplitude occur at 31 km at these stations, in contrast to the literature reported heights and the maximum of the QBO amplitude at SHAR (near to the present observational site) is half of that at Thumba [Reddy et al., 1986]. The time series of zonal wind fluctuations were subjected to Fourier analysis to get the characteristics of AO, SAO and QBO during all the cycles of QBO over the observational period. The annual, semi annual and other shorter period components were removed from the monthly mean zonal wind values. Thus the monthly mean zonal wind values corresponding to QBO uncontaminated by other oscillations were used to estimate the mean flow acceleration. The mean flow acceleration from one month to another is calculated as the difference in the zonal wind speed from one month to the other. This observed mean flow acceleration is compared with the acceleration estimated from the momentum flux divergence of gravity waves.

4.3.4 Mean flow acceleration from gravity wave momentum fluxes

As discussed in Chapter 1, vertically propagating gravity waves dissipates their energy and momentum fluxes to the background wind when they encounter the critical level thereby accelerates the mean flow. The mean flow acceleration \( \frac{\partial \bar{u}}{\partial t} \) caused by the gravity wave divergence is calculated as [Lindzen, 1984]

\[
\frac{\partial \bar{u}}{\partial t} = - \frac{1}{\rho(z)} \frac{\partial \rho(z) \bar{u}'w'(z)}{\partial z}
\]

(4.17)

where \( \rho(z) \) is density at height z and given as

\[
\rho(z) = \rho_0 \exp \left(-\frac{z}{H} \right)
\]

(4.18)

where H is the scale height. Substituting into equation (4.17) and differentiating with respect with to z, leads to

\[
\frac{\partial \bar{u}}{\partial t} \approx - \frac{d}{dz} \left( \bar{u}'w' \right) + \frac{\langle u'w' \rangle}{H}
\]

(4.19)
which gives mean flow acceleration resulting from the divergence of momentum flux of gravity waves. Here H is the scale height calculated from the mean temperature available from lidar observations. The total acceleration produced by the gravity waves is computed as the linear sum of the acceleration produced by the two bands (2-4 hour and 0.5-1 hour band) of periods of gravity waves prominently present in the spectrum.

### 4.3.5 Gravity Wave Forcing Towards QBO

The mean flow acceleration estimated using equation (4.19) for both 0.5-1 hour and 2-4 hour band period of gravity waves are summed together and compared with the observed acceleration computed using NCEP monthly mean zonal winds. Figures 4.12 and 4.13 show such comparison at two pressure levels 20 hPa and 10 hPa respectively. The y-axis at the right hand side of the figures 4.12 and 4.13 denotes the estimated acceleration while that at the left hand side denotes the observed mean flow acceleration and the difference (the scales are not uniform).

From figure 4.12 it is seen that the maximum value of the observed acceleration is \(\sim 10 \text{ ms}^{-1}\text{month}^{-1}\) in the easterly phase while it is \(\sim 9 \text{ ms}^{-1}\text{month}^{-1}\) in the westerly phase at 20 hPa. The maximum of the estimated acceleration from equation (4.12) is \(\sim 2 \text{ ms}^{-1}\text{month}^{-1}\) and \(\sim 1.5 \text{ ms}^{-1}\text{month}^{-1}\) in both westerly and easterly phases respectively. The maximum difference between the observed and estimated acceleration in easterly and westerly phases at 20 hPa are \(\sim 8\) and \(7 \text{ ms}^{-1}\text{month}^{-1}\) respectively. The mean flow acceleration estimated from the divergence of gravity wave momentum fluxes (lidar) and observed from monthly mean zonal wind values (NCEP) are in good agreement during months where the continuous lidar data were available (e.g. during the month no 7-12, 32-39, 45-55, and 76-82 at 20 hPa).
The observed zonal wind acceleration at 10 hPa is $\sim 8$ ms$^{-1}$month$^{-1}$ and $\sim 9$ ms$^{-1}$month$^{-1}$ in the easterly and westerly phases respectively (figure 4.13). The maximum of the estimated acceleration from equation (4.12) is $\sim 2$ ms$^{-1}$month$^{-1}$ and $\sim 1.5$ ms$^{-1}$month$^{-1}$ in both westerly and easterly phases respectively at these pressure levels. The maximum of the difference between the observed and estimated acceleration are $\sim 7$ and 5.5 ms$^{-1}$month$^{-1}$ in both easterly and westerly phases respectively. Similar to 20 hPa, the observed and estimated acceleration are in good agreement during months wherever the continuous lidar data were available (e.g. during the month no 7-12, 32-39, 45-55, and 76-84 at 20 hPa).
Figure 4.13 Comparison of observed (solid line) and estimated acceleration (dotted line with circle) at 10 hPa respectively during April 1998-April 2005. The y-axis at the right hand side denotes the estimated acceleration while that at the left hand side denotes the observed mean flow acceleration and the difference (the scales are not uniform).

It is quite interesting to note that maximum of estimated acceleration in both easterly and westerly phases occur just a month before the transition from one phase to another phase. Another striking feature which can be noted from figures 4.12 and 4.13 is that the estimated and the observed acceleration follow the same trend. Though there are some discrepancies between the mean flow acceleration estimated from the divergence of gravity wave momentum fluxes (lidar) and observed from monthly mean zonal wind values (NCEP) during few months, they are in good agreement during months wherever the continuous lidar data were available (e.g. during the month no 1-3, 7-12, 32-39, 45-55, and 76-84 at both 20 and 10 hPa).

Thus it can be seen that almost 90% of the cases the observed and estimated mean flow acceleration are in good agreement. From figures 4.12 and 4.13 it can be observed that there are some large acceleration and deceleration values found...
during the westerly excursion of the mean zonal winds where we don't have information on the gravity wave momentum fluxes. From figures 4.12 and 4.13 it is also evident that the contribution of gravity wave towards the westerly phase of QBO at 10 hPa is less than 20% while at 20 hPa it varies from ~10-60%. The contribution towards the easterly phase varies from ~10-30% and 10-20% at 10 and 20 hPa respectively. The discrepancy in the observed and the estimated acceleration could be attributed to the contribution from equatorial waves, inertia gravity waves and other longer period gravity waves. It is also seen that gravity wave forcing towards the mean flow acceleration varies significantly from year to year which could be attributed to the inter annual variation in the strength of the gravity wave sources. Studies on gravity waves originated from mesoscale convective systems reported that the gravity waves could account up to 10% of the easterly acceleration of QBO [Pfister et al., 1993]. Studies on zonal forcing in the equatorial stratosphere estimated that 25% of the forcing required for QBO could be provided by gravity waves [Alexander and Holton, 1997]. Piani et al., [2000] using 3D mesoscale model, showed that convectively generated gravity waves could provide up to ~30% of the forcing required for the westerly phase and ~15% of the forcing towards the easterly phase of QBO. The above discussion clearly shows that present results are in well accordance with the earlier modeling studies.

Modeling studies by Alexander and Vincent [2000] reported that the gravity waves contribute significantly to the westerly phase of QBO while forcing towards the easterly phase is small. They concluded that there could be westward propagating gravity waves which were not resolved by the radiosonde observations can play a role in easterly phase of QBO. Thus the present study quantified the role of gravity wave forcing towards generation of the easterly and westerly phases of QBO for the first time using the lidar observations. As there exist other lidar observations over the tropics, it will be very interesting to carry out the present analysis to study the geographical distribution of gravity wave contributions in driving the QBO. It is thus envisaged that the present study will have important implications in studying the wave-mean flow interactions using lidar observations.
4.4 Summary

Using more than 52 months of Rayleigh lidar temperature observations (1998-2005) over a tropical station, momentum fluxes of gravity waves of prominent periods (0.5 -1 hour and 2-4 hour bands) were estimated in the middle atmospheric region. The gravity wave polarization relations were used for this purpose. The advantage of this method is that it estimates the momentum fluxes without measuring vertical velocities. Another advantage is that the momentum fluxes for a particular period of gravity wave can be obtained as the temperature fluctuations with high temporal resolution are available. Since earlier studies of momentum flux estimates applied the same technique to a single profile without knowing a dominant wave frequency. In the present study, the momentum fluxes of 0.5 –1 hour and 2-4 hour bands of periods of gravity waves showed a similar altitude behavior as that of energy. The rate of growth of the wave was found to be different in the stratospheric and mesospheric regions. The seasonal variation of the gravity wave momentum fluxes exhibited a semi annual variation with maxima during equinoctial months and minima during solstitial months. The present work assumes its importance by divulging the seasonal variation in the gravity waves momentum fluxes in the 30-60 km altitude region for the first time over this tropical latitude.

The monthly mean zonal winds from NCEP/NCAR reanalysis data over the observational site were used to study the QBO characteristics in the lower stratospheric region. The comparison of the monthly mean zonal winds from NCEP with in-situ HAB measurements over a low latitude site, Trivandrum, showed very good agreement, which gave further credence to NCEP reanalysis data in those height regions. Contribution of gravity wave forcing towards the generation of four cycles of QBO is estimated and compared with observed mean flow acceleration. From the present analysis, it was seen that on an average ~10-60% and ~10-30% of the forcing to drive the westerly and easterly phases of QBO respectively was from gravity waves, which is in well accordance with earlier modeling studies. It is to be noted that the observational site is not within the main region of QBO and the observation is made over low latitude region. Studies on the gravity wave momentum fluxes in the equatorial region are very
sparse. Most of the earlier studies on the gravity wave momentum fluxes over this region were conducted using VHF radars and the radiosondes, which could not provide gravity wave's drag in the height region where the maximum of QBO amplitude occurs. Thus the present study is first of its kind over this tropical latitude to quantify the gravity wave forcing towards driving the QBO.