6

GRAVITY WAVE FORCING TOWARDS MESOSPHERIC SEMIANNUAL OSCILLATION

6.1 Introduction

Mesospheric Lower Thermospheric (MLT) region is dynamically controlled by the wave activities namely, gravity waves, planetary waves and tides which are mainly originate in the lower atmosphere and dissipate their energy and momentum fluxes in the mesospheric region. Momentum transfer by these waves assumes its importance because their region of deposition is the region of diminished gas density. Though the amount of energy extracted from the lower atmosphere may be small, it could be of tremendous importance to the tenuous upper atmosphere. Theoretical and observational studies revealed a warm winter and cold summer mesopause at high latitudes, and showed that the mesospheric region is thermally far from the radiative equilibrium conditions at solstices [Holton, 1982; Garcia and Solomon, 1985; McIntyre, 1989; Portnyagin et al., 1995]. This departure from the radiative equilibrium is ascribed to the mean meridional circulation from the summer hemisphere to the winter hemisphere with rising and sinking motions over the summer and winter poles respectively. Studies have shown that the transfer of momentum is required to maintain a quasi-steady zonal flow against the coriolis torques generated by this mean meridional flow. It is also found that the residual circulation would collapse unless a wave contribution is there [Plumb, 1982]. The momentum deposition by the dissipating planetary waves can significantly contribute to balance these torques in the winter middle atmosphere and do not appear to contribute to the summer mesospheric momentum budget owing to their absence from the summer hemisphere [Houghton, 1978]. The atmospheric tides, in this regard, are also negligible since observational and theoretical studies have shown their less important role in the mid and high latitudes, unlike low latitudes [Miyahara, 1980]. The internal gravity waves, which are ubiquitous in both winter and summer hemisphere, play an insurmountable role in the dynamics and energetics of the MLT region. Modelling
studies entrenched that the breakdown of the internal gravity waves drives the summer-winter pole residual circulation in the mesosphere \cite{Lindzen, Holton, Matsuno}. In the equatorial region, apart from maintaining the mean circulation, deposition of gravity wave momentum fluxes is believed to be partly responsible for the generation of Mesospheric Semi Annual Oscillation (MSAO). Thus the information about the gravity wave momentum fluxes is essential to understand the momentum budget of the middle atmospheric region in the mid, high and low latitudes. Based on the theoretical studies, measurements of gravity wave momentum fluxes in the MLT region have emerged out as an active area of research interest for the past few decades. In this context, the present study describes a novel method of gravity wave momentum flux estimation in the mesospheric region and their forcing towards the MSAO using SKiYMET meteor wind radar observation over a low latitude station, Trivandrum in detail.

6.2 Gravity Wave Momentum Fluxes in the MLT Region

Recognizing the role of gravity wave momentum fluxes in the MLT region, extensive studies employing several techniques of ground-based radars have been carried out to measure this quantity. First of its kind is a traditional dual beam method proposed by \textit{Vincent and Reid} \cite{Vincent}, in which two or more radar beams each offset from the zenith measure the atmospheric motions by Doppler technique. The momentum flux is calculated from variances of the Doppler velocities thus measured, assuming horizontal homogeneity between two beams over a suitable averaging interval in space and time. Employing the dual beam method, gravity wave momentum fluxes in the MLT region have been estimated in the mid and high latitudes which includes the MF radar at Adelaide, Australia \cite{Reid, Fritts, Murphy}, the SOUSY VHF radar at Andenes, Norway \cite{Reid}, the VHF radar at Poker Flat, Alaska \cite{Fritts, Yuan}, the MU radar at Shigaraki, Japan \cite{Tsuda, Gavrilov, Nakamura}, the Jicamarca MST radar, Peru \cite{Fritts, Hitchman}, the sodium lidar at Starfire Optical Range, New Mexico \cite{Gardner}. In addition to MF and VHF radars, UHF incoherent scatter radar at Arecibo observatory, Puerto Rico has also been
successfully employed to infer the gravity wave momentum fluxes in the MLT region which are otherwise regarded to be unsuitable for the gravity wave studies because of their long integration time in the MLT region [Zhou and Morton 2006; Janches et al., 2006; Fritts et al., 2006]. However, all these measurements have been made use of VHF radars, which have limited seasonal coverage, and MF radars with narrow beams, which are relatively rare. An alternative method for determining the momentum fluxes using MF broad beam interferometric radars was devised by Thorsen et al., [1997]. Different from MF and VHF radars, Hocking [2005] introduced a novel method employing meteor radars to estimate the gravity wave momentum fluxes for the first time. The advantage of this method is that it does not require any beam formation and uses the meteor echoes to estimate the momentum fluxes in an all sky manner. All these methods are discussed in detail in section 6.5.

Apart from radar measurements, rocket borne chaff measurements of horizontal and vertical winds [Meyer et al, 1989], intensity variances in the airglow imagers [Swenson et al., 1999; Gardner et al., 1999; Tang et al., 2002, 2005; Espy et al., 2004, 2005], satellite measurements of departure of mean state from uniform zonal flow and/or radiative equilibrium conditions [Smith and Lyjak, 1985] and satellite based CRISTA temperature measurements [Ern et al., 2004] were also effectively used in determining the gravity wave momentum fluxes in the MLT region. All of these studies demonstrated the potential of ground-based, in-situ and satellite-based instruments in measuring the gravity wave momentum fluxes in the MLT region thereby improved our understanding of the role of gravity waves in altering the dynamics of the MLT region.

A detailed comparison of the momentum fluxes of gravity waves (few minutes to few hours) measured using different techniques at various geographical locations is given in Table 6.1. It is to be noted that the magnitudes shown in Table 6.1 do not correspond to the same season and hence shows the large variability. It is evident from Table 6.1 that momentum flux measurements over the equatorial/low latitude mesospheric region is very sparse and thus the present study assumes its importance by reporting the gravity wave momentum fluxes in the low latitude mesospheric region.
<table>
<thead>
<tr>
<th>Geographical Location</th>
<th>Instrument</th>
<th>Height region</th>
<th>Gravity wave period</th>
<th>Zonal momentum flux range</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arecibo observatory (18°N, 67°W), Puerto Rico</td>
<td>Dual-beam incoherent scatter radar</td>
<td>65-95 km</td>
<td>50 min-2 hours</td>
<td>10-50 m²s⁻²</td>
<td>[Zhou and Morton, 2006; Fritts et al., 2006]</td>
</tr>
<tr>
<td>Socorro, New Mexico (34°N, 107°W)</td>
<td>SKiYMET radar</td>
<td>82-98 km</td>
<td>2-3 hours</td>
<td>10-50 m²s⁻²</td>
<td>[Hocking, 2005]</td>
</tr>
<tr>
<td>Starfire Optical Range, New Mexico (35°N, 107°W)</td>
<td>Airglow imager Na Lidar</td>
<td>85-100 km</td>
<td>4 min-2 hours</td>
<td>-11.9±0.49 m²s⁻²</td>
<td>[Gardner et al., 1999; Tang et al., 2002]</td>
</tr>
<tr>
<td>Shigaraki, Japan (35°N, 136°E)</td>
<td>MU radar</td>
<td>60-90 km</td>
<td>5 min-2 hour</td>
<td>1 m²s⁻²</td>
<td>[Tsuda et al., 1990; Nakamura et al., 1993]</td>
</tr>
<tr>
<td>Poker flat (65°N, 147°W)</td>
<td>MST radar</td>
<td>80-90 km</td>
<td>5 min-few hours</td>
<td>5-15 m²s⁻²</td>
<td>[Fritts and Yuan, 1989]</td>
</tr>
<tr>
<td>Jicamarca, Peru (12°S, 77°W)</td>
<td>MST radar</td>
<td>70-85 km</td>
<td>~1 hour</td>
<td>2-8 m²s⁻²,</td>
<td>[Hitchman et al., 1992]</td>
</tr>
<tr>
<td>Adelaide, Australia (35°S, 138°E)</td>
<td>Dual beam Doppler radar</td>
<td>80-90 km</td>
<td>~3-6 hours</td>
<td>5 -16 m²s⁻²</td>
<td>[Vincent and Reid, 1983]</td>
</tr>
<tr>
<td>Rothera (67°S, 68°W)</td>
<td>Airglow images and MF radar</td>
<td>90 km</td>
<td>High frequency gravity waves</td>
<td>-32 m²s⁻², -7.5 m²s⁻²</td>
<td>[Espy et al., 2004, 2005]</td>
</tr>
</tbody>
</table>

**Table 6.1** Comparison of gravity wave zonal momentum fluxes measured using different techniques at various geographical locations.
Most of the above mentioned ground based studies are limited to mid and high latitudes. Beyond any doubt it can be stated that studies on gravity wave momentum fluxes in the equatorial MLT region are very limited.

6.3 Characteristics of Mesospheric Semiannual Oscillation

As discussed in the previous chapter, it is well established that amplitude of the semiannual oscillation maximizes in the stratopause and mesopause regions with minimum around 64 km [Hirota, 1978; Hamilton, 1982]. Among these, MSAO in zonal winds is very well studied using ground-based radars, in-situ rocket observations and satellite measurements [Reed, 1966; Garcia et al., 1997]. The MSAO is characterized by maximum easterlies around 80 km near the equinoxes and maximum westerlies around 85 km near solstices. The alternating wind regimes in the MSAO descend at the rate of ~6 km/month with considerable inter-annual variability unlike SSAO. It is also reported that the MSAO is approximately three months out of phase with SSAO [Hirota, 1978; Hamilton, 1982]. Later using the Solar Mesospheric Explorer (SME), Garcia and Clancy [1990] showed the presence of MSAO in temperature. Over the present observational site, SAO in temperature, zonal and meridional winds in the lower thermospheric region were documented using meteor wind radar observations. [Reddi et al., 1993; Reddi and Ramkumar, 1997]. Recent satellite and radar observations have suggested that the MSAO is modulated by the stratospheric QBO. It is also shown that the modulation is only apparent during the SAO easterly phase, which is considerably stronger when QBO winds are easterly than when they are westerly. No such modulation is seen in the westerly phase of MSAO [Garcia and Sassi, 1999]. Decades back, MSAO was less explored due to infrequent and discontinuous rocketsonde measurements to probe the upper mesospheric regions unlike the stratospheric region, which hindered the scientific community from neither defining the climatology nor documenting the inter annual variability. Later with increasing number of MF, VHF and meteor radars and satellites it is made plausible to investigate the MSAO characteristics and its seasonal variations [Garcia et al., 1997].
Figures 6.1 (a) and (b) show the height profile of the amplitudes and phases of MSAO measured using HRDI wind data (solid line), MF radar (dashed line) at Christmas Island (2°N, 157°W), and Ascension Island (8°S, 14°W) rocketsondes data (dotted line) [after Burrage et al., 1996]. This study reported that the maximum MSAO amplitude occurs at 82 km with magnitude in the range of 30 to 35 ms\(^{-1}\) [Hirota, 1978; Burrage et al., 1996] while the MF radar observations over Christmas Island reported the maximum amplitude of 10 ms\(^{-1}\) around 84 km [Vincent, 1993]. The vertical structure of the MSAO phase depicted in figure 6.1 (b) shows decreasing trend with height in the 80-90 km height region while it shows increasing trend above 90 km altitude. The similar trend is observed in most of the MSAO cycles investigated in the present work.

Studies over a nearby low latitude station Tirunelveli showed maximum MSAO amplitude as 25 ms\(^{-1}\) at 84 km and the constant phase structure above 86 km [Rajaram and Gurubaran, 1998]. Earlier studies by Reddi and Ramkumar [1997] over Trivandrum reported that there was nearly constant amplitude of ~15 ms\(^{-1}\) around the mesopause. Their finding also showed that the phase profile observed at Trivandrum agreed well with that of CIRA 1986 profile while differed from Ascension Island by nearly three months. Their study revealed that the MSAO characteristics over Trivandrum were different from those observed over other low latitude stations like Ascension Island, Christmas Island and Kwajalein and suggested that this difference
could be due to inter annual variability since the data sets corresponding to different years were used for comparison.

6.4 Forcing mechanisms involved in the generation of MSAO

In the past few decades, considerable amount of theoretical and modeling work have been devoted towards the understanding of forcing mechanisms of MSAO. All these studies showed that the easterly and westerly phases of the MSAO are also wave driven similar to SSAO. *Lindzen* [1981] suggested that winds in the troposphere and stratospheric regions play a crucial role in limiting the phase speeds of the internal gravity waves which reach the mesospheric regions. Based on the *Lindzen*’s hypothesis, *Dunkerton* [1982] proposed a forcing mechanism for the MSAO in terms of the breaking of gravity waves and Kelvin waves. He suggested that the selective transmission of gravity and Kelvin waves by the SSAO is responsible for driving the MSAO thereby ruled out the in-situ forcing of MSAO. *Sassi and Garcia* [1997] using an equatorial beta-plane model showed that the major part of the forcing of easterly phase of MSAO is by inertia gravity waves which are forced by convective heating in the troposphere while in the case of westerly phase, intermediate scale Kelvin waves also play a significant role. It is to be noted that the Kelvin waves are eastward propagating and momentum deposition of which can lead to the westerly acceleration of MSAO.

Earlier studies using a global-scale numerical spectral model of the middle atmosphere, which incorporates the realistic parameterization scheme for gravity wave momentum flux deposition based on the Doppler spread theory [*Hines*, 1993], *Mengel et al.*, [1995] and *Mayr et al.* [1997] concluded that gravity waves might contribute significantly to QBO and SAO in the upper stratosphere and mesosphere. In a recent seminal work, *Richter and Garcia* [2006] have examined the forcing of MSAO using the Whole Atmosphere Community Climate Model (WACCM2). The authors showed that near solstices, gravity waves are the largest forcing term of MSAO, which are out of phase with the gravity wave forcing in the stratospheric region. Though these studies confirmed the selective transmission of waves through lower level background wind, none of them quantified the relative contribution of these waves towards the forcing of MSAO. **It should be emphasized that the above-mentioned studies do not make definitive**
statements about the nature of the waves that drive the SAO. In particular, they do not help to distinguish between the relative contributions of mesoscale waves [Mengel et al., 1995; Mayr et al., 1997], medium-scale waves [Sassi and Garcia, 1997], or large-scale waves [Dunkerton, 1982]. Apart from gravity waves and Kelvin waves, the role of diurnal tides in the forcing of easterly phase of MSAO is also well recognized [Lindzen, 1981].

Modeling studies by Miyahara and Wu [1989] showed that the dissipation of westward propagating diurnal tides can generate significant mean zonal winds in the mesopause region and the semi annual modulation of the tidal amplitude could be related to the MSAO. Studies using UARS satellite data by Lieberman and Hays [1994] estimated the mean flow acceleration induced by the dissipating diurnal tides in the lower thermosphere. Studies using MF radar observations over low-latitude site, Tirunelveli (8.7°N, 77.8°E) suggested that the short-term tidal variability could contribute to the variation of the mean westward flow associated with the MSAO, either directly or indirectly through the gravity wave-tidal interactions [Gurubaran and Rajaram, 2001]. However, this study could not provide any quantitative estimation of the gravity wave forcing towards the mean zonal flow. Nevertheless, the relative roles of these waves and their variability in forcing the MSAO are yet to be quantified.

Thus the information about the gravity wave momentum fluxes is essential to understand the momentum budget of the middle atmospheric region in the low, mid, and high latitudes. Measurements of gravity wave momentum fluxes in the MLT region have emerged out as an active area of research interest for the past few decades. The central objective of the present study is to estimate the momentum fluxes of the gravity waves of periods less than 2-3 hours and of typical horizontal wavelengths of few tens of kilometres to few hundred kilometres, hence the name mesoscale gravity waves, over a low-latitude site, Trivandrum using the meteor radar observations for the first time.
6.5 Estimation of Momentum Fluxes Using Radars

For many decades radars have been extensively used to measure the winds in the tropospheric and mesospheric regions with unprecedented spatial and temporal resolution. Recognizing the role of gravity wave momentum fluxes, several methods have been proposed to measure this quantity either directly or indirectly through the radar-measured winds.

6.5.1 Direct Approach Method

The difficulty of determining the gravity wave momentum fluxes using radars lies in the measurements of vertical winds with good accuracy. With the advent of VHF radars it is made possible to measure the vertical winds directly with good accuracy. Thus the simultaneous measurements of horizontal and vertical winds by MST radars integrated over a suitable time and space gives the vertical flux of horizontal momentum. The time series of the perturb ation components of $u$ and $w$ ($u'$ and $w'$) are obtained using a suitable filtering of the original time series for isolating a particular frequency or a frequency band of interest. Further, the products $u'w'$ are formed and averaged over a suitable length of time.

6.5.2 Symmetric Beam Method

Vincent and Reid [1983] proposed a novel method to estimate the gravity wave momentum fluxes using HF radars. In this method, two or more radar beams each offset from the zenith measure the atmospheric motions by Doppler technique. The momentum flux is calculated from variances of the Doppler velocities thus measured, assuming horizontal homogeneity between two beams over a suitable averaging interval in space and time. The momentum flux in a vertical plane is obtained using two radial radar beams in that plane, pointing at symmetric zenith angles, $+\theta$ and $-\theta$

$$
\frac{u'w'}{2\sin2\theta} = \frac{r_{+\theta}^2 - r_{-\theta}^2}{2\sin2\theta}
$$

(6.1)

where $u'$ and $w'$ represent the horizontal and vertical perturbation velocities and $r_{+\theta}$ and $r_{-\theta}$ represent radial perturbation velocities in the two beams. The advantage of the symmetric
beam method is that it does not require vertical beam measurement for the momentum flux estimates. Another approach [e.g., Fukao et al., 1988] uses the product of the perturbation vertical wind component measured directly with the vertical radar beam and the horizontal velocity derived from the vertical and a radial beam, to give the momentum flux in the vertical plane, defined by the two beams.

$$\overline{u'w'} = \frac{w'(r_\theta - w' \cos \theta)}{\sin \theta}$$  \hspace{1cm} (6.2)

where \(w'\) represents the vertical beam measurement.

### 6.5.3 Hybrid Method

Worthington and Thomas [1996] proposed a method, which uses a vertical beam to measure the perturbations in the vertical velocities and a pair of radial beams for measuring the horizontal velocities.

$$\overline{u'w'} = \frac{w'(r_\theta - r_\theta)}{2 \sin \theta}$$  \hspace{1cm} (6.3)

This method is ‘Hybrid’ of the equations (6.2) and (6.3) and hence called hybrid method.

### 6.5.4 Time Domain Interferometry Method

A new method to measure the mean winds using MF radar apart from conventional Spaced Antenna Full Correlation Analysis (SA-FCA) was first devised by Vandepeer and Reid [1995] based on the Time Domain Interferometry (TDI), which employs a single vertical beam for this purpose. This method is further refined and used by Thorsen et al., [1997] and applied to Urbana MF radar data to measure the variances and momentum fluxes. This method may be viewed as the generalization of the Velocity Azimuth Display (VAD) technique by Frisch et al., [1989] and symmetric beam method by Vincent and Reid [1983] and is applicable to MF radar with a single vertically pointed beam.
6.5.5 Meteor Radar Method

Unlike the traditional dual beam method this method uses the meteor echoes to measure the gravity wave momentum fluxes in the MLT regions. Meteor radars are used to determine the horizontal winds by utilizing the radio reflections from the meteor trails in the MLT region. The radar measures the Doppler shifts in the frequency of meteor echoes and meteor locations (angular position and range \((\theta, \phi \text{ and } R)\)) for every meteor detected where \(\theta\) is the angle from zenith, \(\phi\) is the azimuthal angle anticlockwise from due east and \(R\) is the range in spherical coordinates. The radial velocity of each meteor \((u_{rad})\) is determined using the Doppler frequency measured. Once a large number of radial velocities are collected they are clustered into specific height and time bins. To calculate the mean wind an all-sky fit of radial velocities is performed using least squares fitting procedure where the residual is given by

\[
\sum (u_{rad} - u_{radm})^2 \quad (6.4)
\]

where \(u_{radm}\) is the mean radial velocity expected if the winds were uniform in a horizontal plane and is given by

\[
u_{radm} = U \sin \theta \cos \phi + V \sin \theta \sin \phi + W \cos \theta \quad (6.5)
\]

where \(U\) is the mean zonal, \(V\) is the mean meridional and \(W\) is the mean vertical winds respectively. The summation in equation \((6.4)\) is over all the detected positions. However, in reality the wind is not uniform, and the measured radial velocity \(u_{rad}\) usually differs from the value of \(u_{radm}\).

\[
u'_{rad} = u_{rad} - u_{radm} \quad (6.6)
\]

Assuming the differences in the radial velocities are mainly due to gravity waves, an all sky fit of \(u'^{2}_{rad}\) is performed and the residual is given by

\[
\Lambda = \sum (\nu'_{rad})^2 - (\nu'_{radm})^2 \quad (6.7)
\]

where \(u'^{2}_{radm}\) is the modelled radial velocity variances at position \((\theta, \phi)\) and is given by
\[ \nu_{\text{radn}} = u' \sin \theta \cos \phi + v' \sin \theta \sin \phi + w' \cos \theta \]  

(6.8)

where \( u' \), \( v' \), and \( w' \) are the fluctuating zonal, meridional and vertical wind velocities respectively, which could be due to gravity wave and turbulent motions.

Squaring this term and substituting into equation (6.7) we get

\[
\Lambda = \sum (\nu'_{\text{radn}})^2 - \left( \frac{u'^2 \sin^2 \theta \cos^2 \phi + v'^2 \sin^2 \theta \sin^2 \phi + w'^2 \cos^2 \theta + u'v' \sin \theta \cos \phi \sin \phi + 2u'w' \sin \theta \cos \theta \cos \phi + 2v'w' \sin \theta \cos \theta \sin \phi}{2} \right)^2
\]

(6.9)

where the summation is over all detected meteor positions within a user prescribed height and time interval. To minimize \( \Lambda \), we partially differentiate equation (7) with respect to \( u'^2 \), \( v'^2 \), \( w'^2 \), \( u'v' \), \( u'w' \) and \( v'w' \), and set each derivative to zero. For example, differentiating with respect to \( u'^2 \), we obtain

\[
2\sum (\nu'_{\text{radn}})^2 - \left( \frac{u'^2 \sin^2 \theta \cos^2 \phi + v'^2 \sin^2 \theta \sin^2 \phi + w'^2 \cos^2 \theta + u'v' \sin \theta \cos \phi \sin \phi + 2u'w' \sin \theta \cos \theta \cos \phi + 2v'w' \sin \theta \cos \theta \sin \phi}{2} \right) \sin^2 \theta \cos^2 \phi = 0
\]

(6.10)

Similarly differentiating with respect to all 6 parameters a matrix equation is obtained, assuming that the parameters \( u'^2 \), \( v'^2 \) etc. are all uniform across the field of view.
\[
\begin{array}{cccc}
\Sigma \sin \theta & \Sigma \sin \theta \cos \phi & \Sigma \sin \theta \cos \phi & \Sigma \sin \theta \\
\cos \phi & \Sigma \sin \theta \cos \phi & \Sigma \cos \theta & \cos \phi \\
\sin \phi & \sin \phi & \Sigma \sin \theta \cos \phi & \cos \phi \\
\Sigma \sin \theta \cos \phi & \Sigma \cos \theta & \Sigma \cos \theta & \Sigma \sin \theta \cos \phi \\
\cos \phi & \Sigma \sin \theta \cos \phi & \Sigma \cos \theta & \Sigma \sin \theta \cos \phi \\
\sin \phi & \Sigma \sin \theta \cos \phi & \Sigma \cos \theta & \Sigma \sin \theta \cos \phi \\
\Sigma \sin \theta \cos \phi & \Sigma \cos \theta & \Sigma \cos \theta & \Sigma \sin \theta \cos \phi \\
\cos \phi & \Sigma \sin \theta \cos \phi & \Sigma \cos \theta & \Sigma \sin \theta \cos \phi \\
\end{array}
\]

\[
\begin{bmatrix}
u^2 \\
v^2 \\
w^2 \\
uv \\
wv \\
vw \\
\end{bmatrix}
= \begin{bmatrix}
\Sigma u_{ad}^2 \sin \theta \\
\Sigma u_{ad}^2 \cos \theta \\
\Sigma u_{ad}^2 \sin \theta \\
\Sigma u_{ad}^2 \cos \theta \\
\Sigma u_{ad}^2 \sin \theta \\
\Sigma u_{ad}^2 \cos \theta \\
\end{bmatrix}
\]

(6.11)
This equation can readily be inverted to produce an estimate for the parameters $\overline{u'^2}, \overline{v'^2}, \overline{w'^2}, \overline{uw'}, \overline{uw}$ and $\overline{vw'}$. Thus the radial velocity variances measured by the meteor radar are used to determine the momentum fluxes of the gravity waves [Hocking, 2005].

### 6.6 Methodology Followed in the Present Analysis

As discussed in Chapter 2, meteor radar receives echoes in an all sky manner. For the present study meteors in the zenith angles 15° to 45° are chosen since more number of meteors occur in this range. The meteors detected at zenith angles less than 15° are excluded as in the normal meteor studies. Since the vertical velocity determinations are involved meteors detected beyond the zenith angles 45° are also not considered for the present study. It should be noted that in the symmetric beam method using VHF and MF radars, off-vertical beams of 10° to 15° are employed since relative contributions from the vertical and horizontal velocities to the radial velocity are approximately in the ratio of 4:1. At 30° the ratio is 1.7:1 and at 45° it is 1:1. It can be seen that that meteor radars are less sensitive to vertical velocities, which can still be, compensated by achieving higher count rates than MF radars.

While deriving winds from meteor wind radar typically 7 to 9 meteors are needed in a particular time and height bin for reliable mean wind estimation. Since the present study involves the second order estimates more than 30 meteors are needed in a particular height-time bin. Only unambiguous meteors are used for the present study. The averaging time bins actually cover 90 min, covering 45 min before and 45 min after the nominal time, and the nominal time is shifted in steps of 1 h. The averaging time is so chosen, as discussed earlier, in order to avoid the lesser meteor counts in the afternoon and late afternoon hours. With these scattering volume and averaging interval, the present study thus focuses on the gravity waves of periods less than 2-3 hours with horizontal and vertical wavelengths of less than 180 km and 5-10 km respectively. The choice of scattering volumes and averaging time could be varied to study the gravity waves of different characteristics.
6.7 Results and Discussion

6.7.1 Altitude Profiles of Gravity Wave Momentum Fluxes

Using the method discussed in section 6.5.5, the height profile of day-mean vertical flux of zonal momentum \( (u'w') \) is estimated from equation (6.11) using the data collected round the clock during the period June 2004-May 2007. A typical height profile of \( u'w' \) is shown along with day-mean zonal wind during April 2007 in figure 6.2. It can be seen from the figure that the zonal momentum flux ranges between \(-25 \text{ m}^2\text{s}^{-2}\) to \(-2 \text{ m}^2\text{s}^{-2}\) in the 82-98 km height region. However, further analysis showed that the daily mean exhibits larger variability with magnitudes as large as \(-30-40 \text{ m}^2\text{s}^{-2}\), while hourly momentum flux magnitudes were of the order of \(-60 \text{ m}^2\text{s}^{-2}\).

![Figure 6.2](image-url)  
*Figure 6.2 Altitude profiles of day-mean zonal wind (dashed) and zonal momentum fluxes (solid) of short period gravity waves for a typical day in the month of April 2007.*
Figure 6.2 clearly shows that the momentum flux are in the westerly direction in the 82-91 km altitude region and changes from westerly to easterly above 91 km altitude region on this particular day with mean zonal velocity varying from ~60 ms\(^{-1}\) to ~25 ms\(^{-1}\) in the 82-98 km altitude region. Interestingly, the mean zonal wind in the 82-91 km altitude is in the easterly direction and changes its direction to westerly above 92 km. It can be noted from the figure that both momentum fluxes and mean zonal winds are in exactly opposite direction. Such negative correlations were also reported by earlier studies by Fritts and Vincent [1987] and Frits and Yuan [1989]. They reported that the negative correlations could be attributed to the modulation of gravity wave fluxes by the low frequency tidal motions which in turn contribute to the global tidal variability. It is also noted from the figure that direction change in the momentum fluxes occur prior to the mean zonal flow.

![Figure 6.3](image_url)

**Figure 6.3** Altitude profiles of the variances of the zonal (triangle), meridional (circle) and vertical (star) winds of short period gravity waves for a typical day in the month of April 2007.
Figure 6.3 shows the height profile of day mean variances of three wind components along with standard errors on the same day in April 2007. The variances of the zonal, meridional and vertical wind components are estimated using equation (6.11). The variance of the zonal and meridional winds ranges from 100 to 500 m$^2$s$^{-2}$ while that of the vertical wind is less than 100 m$^2$s$^{-2}$ in 82-98 km height region. Studies using MF radar observations over mid and high latitudes reported that monthly mean variance of 1-6 hour band of gravity waves between 50 to 150 m$^2$s$^{-2}$ in the 61-73 km altitude region while it was 100 to 250 m$^2$s$^{-2}$ in the 76-88 km altitude region [Manson et al., 1997]. It is well established that the amplitude of gravity waves increases with height owing to the conservation of energy, which is evident from figure 6.3.

6.7.2 Seasonal Variation of Gravity Wave Momentum Fluxes

Using meteor radar data collected over three continuous years (2004-2007), the seasonal variations in the gravity wave momentum fluxes over this region are investigated. Figures 6.4 (a) and (b) show the composite seasonal variation of the vertical fluxes of zonal ($u'w'$) and meridional ($v'w'$) momentum for the 2-3 hours period gravity waves over the three years of observations in the height region 82-91 km. From these figures it can be seen that the magnitude of $u'w'$ varies from -10 m$^2$s$^{-2}$ to 10 m$^2$s$^{-2}$ while $v'w'$ varies from -5 m$^2$s$^{-2}$ to 5 m$^2$s$^{-2}$. Semi annual variation is clearly seen with maxima around equinoxes and minima around solstices in the 82-91 km height region.

The momentum fluxes in the winter months are found to be more than that during summer months. The $u'w'$ during the vernal equinox is found to be more than the autumnal equinox at all heights except at 82 km. In the case of $v'w'$ maximum values are found to be almost equal during equinoxes. The maximum value of $u'w'$ and $v'w'$ varies with height. It is seen from the figure that maximum value of $u'w'$ occurs during April at 85, 88 and 91 km while it is during May at 82 km. The maximum value during second half of the year occurs during September at higher altitudes while it is during October and August at 82 km and 85 km respectively. In the case of $v'w'$ the maximum occurs at
September at all heights while it is either during March or April during vernal equinoxes. The $u'w'$ and $v'w'$ at 82 km is found to be maximizing during May.

Figure 6.4 Seasonal variation in the vertical flux of a) zonal and (b) meridional momentum of short period gravity waves in the 82-91 km height region respectively.
Earlier studies using MU radar showed clear annual variation in gravity wave momentum fluxes with eastward values during summer and westward values during winter in the 60-85 km height region [Tsuda et al., 1990]. Rocket observations in the middle atmospheric region between 77°N - 8°S over several years showed that the gravity wave activity exhibits annual variation with winter maximum at high latitudes and semiannual variation with equinoctial maximum at low latitudes [Hirota, 1984]. Studies on gravity wave climatology in the mesopause region using MF radar brought out that low and medium frequency gravity wave activity varied mainly in semi annual manner although an annual component was also present with maximum during winter and minimum during summer [Vincent and Fritts, 1987]. This particular study also reported that the minima in the wave activity coincided with reversal of zonal circulations while maximum occurred at times when zonal winds were stronger in the middle atmospheric region.

Manson et al., [1997] using MF radars at mid and high latitudes reported that semi annual oscillation dominates in the case of 10-100 min band while annual oscillation is seen in the case of 1.5-6 hour band of gravity waves. The authors attributed this distinct feature in the wave activity between two bands of periods of gravity waves to Doppler shifting. Thorsen and Franke [1998] brought out the climatology of the mesospheric gravity wave activity derived from 5 years of MF radar observations at Urbana, Illinois (40°N, 88°W). Their study reported that the gravity wave activity exhibits a semiannual oscillation in the lower mesosphere and relatively little change with season in the upper mesosphere. Studies using sodium lidar observations in the 85-100 km height region at Starfire Optical Range showed strong seasonal variations in the horizontal momentum fluxes [Gardner and Liu, 2007]. As discussed in Chapter 3, the seasonal variations of the gravity wave momentum fluxes in the stratospheric region also exhibits a semiannual variation with equinox maximum and solstitial minimum. The present study also clearly shows the semi annual variation in the gravity wave activity in the low latitude MLT region in contrast to mid and high latitudes in the MLT region as depicted in figure 6.4.
6.7.3 Characteristic Features of Mesospheric Semiannual Oscillation (MSAO) over Trivandrum

As SAO in the stratospheric region is extensively discussed in the Chapter 5, the MSAO alone is discussed here. The meteor wind radar measures the horizontal winds in the 82-98 km altitude region with temporal and spatial resolution of 1 hour and 3 km respectively round the clock. The determination of horizontal winds using meteor radar is discussed in Chapter 2. The hourly values of both zonal and meridional winds are averaged over a day to get daily mean values which are further averaged over a month to yield monthly mean values. Figure 6.5 shows the monthly mean (a) zonal and (b) meridional winds in the 82-98 km height region during June 2004-May 2007. It should be noted that zonal and meridional wind values are shifted by 50, 100, 150, 200, and 250 ms⁻¹ at 85, 88, 91, 94 and 98 km respectively. A strong MSAO is clearly seen in the zonal winds in the height region of 82-90 km (figure 6.5 (a)). However, in the 91-98 km height region, easterly winds are prominently present with weak semiannual oscillation (SAO).

These observations are entirely consistent with earlier studies reported using HRDI and MF radar observations, which showed the presence of strong SAO up to 90 km and easterly winds with weak SAO above 90 km [Garcia et al., 1997]. The latitudinal behaviour of the SAO exhibited that the easterly phase of SAO is equatorially confined and nearly symmetric about the equator while westerlies appear as the extension of the mid-latitude winter westerlies. Lieberman and Hays [1994] suggested that the presence of easterlies above 90 km could be due to the easterly momentum deposition by the propagating diurnal tides. However, there is no prominent SAO in the meridional winds in the entire height domain as shown in figure 6.5(b). Reddi and Ramkumar [1997] using meteor radar observations over the present observational site have shown that SAO amplitude in meridional wind is very small (less than 5 ms⁻¹) as compared to that of the zonal wind.
Figure 6.5 Time-height section of (a) mean zonal and (b) meridional winds respectively during June 2004-May 2007 over Trivandrum. The plots at each height are shifted by 50 ms\(^{-1}\).
Six cycles of MSAO in zonal winds are chosen for the present analysis starting with June-November 2004 as the first cycle and subsequent chosen cycles are given in Table 6.2.

<table>
<thead>
<tr>
<th>Cycle</th>
<th>Height (km)</th>
<th>Month of constant phase</th>
<th>Westerly</th>
<th>Easterly</th>
</tr>
</thead>
<tbody>
<tr>
<td>First (Jun-Nov04)</td>
<td>82 85 88</td>
<td>July</td>
<td></td>
<td>September</td>
</tr>
<tr>
<td>Second (Dec04-May05)</td>
<td>82 85 88</td>
<td>January</td>
<td></td>
<td>April</td>
</tr>
<tr>
<td>Third (Jun-Nov05)</td>
<td>82 85 88</td>
<td>June</td>
<td></td>
<td>September</td>
</tr>
<tr>
<td>Fourth (Dec05-May06)</td>
<td>82 85 88</td>
<td>December</td>
<td></td>
<td>February</td>
</tr>
<tr>
<td>Fifth (Jun-Nov06)</td>
<td>82 85 88</td>
<td>June</td>
<td></td>
<td>September</td>
</tr>
<tr>
<td>Sixth (Dec06-May07)</td>
<td>82 85 88</td>
<td>January</td>
<td></td>
<td>April</td>
</tr>
</tbody>
</table>

Table 6.2 Details of MSAO discussed in present study.

During the first cycle, the westerly maximum occurred during July 2004 while easterly maximum during September 2004. In almost all the cycles westerly maximum is during June and January while easterly maximum is during September and April. From figure 6.4, it can be seen that the easterly maximum during autumnal equinoxes are much weaker than those during vernal equinoxes consistent with Garcia et al., [1997]. The amplitude of MSAO during June 2005-May 2006 is relatively weaker than that during June 2004-May 2005 and June 2006-May 2007. Thus, considerable interannual variations in the MSAO amplitudes are observed over this observational site. Earlier studies using the UARS satellite observations and later, MF radar observations revealed interannual variability in the mesospheric winds and attributed this variability to
the stratospheric QBO manifestation in the mesospheric zonal winds. [Burrage et al., 1996; Garcia et al., 1997; Rajaram and Gurubaran, 1998].

To compare the phase of MSAO with SSAO, the monthly mean zonal wind measured at 82 km from meteor radar observations is compared with rocketsonde derived zonal wind observations at 50 km over the present observational site and is shown in figure 6.6. As discussed in Chapter 4, the rocketsonde observations were carried out under MIDAS program during the observational period, which provides zonal and meridional winds in the 25-65 km height region. MSAO is always out of phase with SSAO as shown in figure 6.6, which further confirms the known characteristics of measured winds in the middle atmospheric region. The out of phase relationship between the SSAO and MSAO is attributed to the critical level filtering of the vertically propagating gravity waves and equatorial waves in the stratospheric region which is believed to be the main driving mechanisms of the MSAO. It is well known that easterly propagating waves will be filtered out in the easterly mean flow and propagates without any attenuation in the westerly mean flow. Thus if the SSAO is in the easterly (westerly) direction, westerly (easterly) propagating waves will propagate vertically up and deposit their momentum for the generation of westerly (easterly) acceleration of MSAO.

![Graph showing monthly mean zonal winds at 50 km (dotted line) and 82 km (solid line).](image)

**Figure 6.6** Monthly mean zonal winds at 50 km (dotted line) and 82 km (solid line).
The hourly zonal and meridional winds in the 82-98 km region were temporally averaged to get the monthly mean zonal and meridional winds for the period of June 2004- May 2007 which is shown in figure 6.5. The errors involved in the monthly mean zonal and meridional winds are ~0.1 ms\(^{-1}\). From the monthly mean zonal winds, annual oscillation component was removed to get the zonal wind fluctuations. The time series of annual component removed zonal wind fluctuations were then subjected to Fourier analysis to get the characteristics of MSAO such as amplitude and phase for six cycles over three years of observational period. Figures 6.7 (a)-(f) show the height profiles of amplitude (left panel) and phase (right panel) of MSAO during the six MSAO cycles considered for the present study. The standard errors in the amplitude and phase are estimated using the error propagation formula [Whittaker and Robinson, 1965] which is elaborated in section 3.3.3.2 of Chapter 3. From these figures 6.7 (a)-(f), it can be noted that the amplitude of MSAO shows considerable degree of inter-annual variability with magnitudes ranging from 10 to 40 ms\(^{-1}\). There is a significant variability in the vertical structure of amplitude and phase in all the six MSAO cycles.

A decrease in amplitude with height is seen in all the cycles except fourth and fifth MSAO cycles which show an increase in amplitude with height. The phase is almost constant in the 82-91 km height region, while in the 94-98 km height region an increasing trend is seen in the first and second MSAO cycles [see figures 6.7 (a) and (b)]. The phase structure during third cycle (figure 6.7 (c)) increases in the 82-98 km altitude region while it decreases above 88 km region in the fourth and fifth cycles [figure 6.7 (d) and (e)]. During sixth cycle in figure 6.7 (f), decrease in phase with altitude is seen in the 82-88 km altitude regions and above that increase with height is observed. Inter annual variability in the MSAO amplitude is clearly seen in the present observations also, which is in well accordance with the previous studies as discussed in introduction (section 6.3).
Figure 6.7 Altitude profiles of amplitude and phase of MSAO during (a) first (b) second (c) third (d) fourth (e) fifth and (f) sixth cycles during June 2004-May 2007. Refer Table 6.2 for details of MSAO cycles.
6.7.4 Wave-Mean Flow Interaction

There are considerable number of studies on gravity wave forcing in the tropical and extra tropical sites in the lower stratospheric and mesospheric regions using radars. As discussed in Chapter 4, the mean flow acceleration produced by the gravity waves is calculated from the divergence of momentum flux using the equation

$$\frac{\partial u}{\partial t} \approx - \frac{d}{dz} \left< u'w' \right> + \frac{\left< u'w' \right>}{H}$$

(6.12)

where $H$ is the scale height and taken as 6 km in the 82-98 km altitude region.

6.7.4.1 Mean Flow Acceleration from Monthly Mean Zonal Winds

The monthly mean zonal winds during June 2004-May-2007 were used to calculate the mean flow acceleration. The errors in the mean flow acceleration calculated from the monthly mean winds also would be small since the standard errors involved in the monthly mean winds are very small. The mean flow acceleration from one month to the other was calculated where the phase (corresponding to maximum amplitude) of MSAO remained constant. The month of the maximum phase during the westerly and easterly phases of all six MSAO cycles is given in Table 6.2. The maximum of the observed acceleration in all the cycles in the westerly phase varies from $-20$ ms·month$^{-1}$ to $-40$ ms·month$^{-1}$ while in the easterly phase it ranges from $-5$ ms·month$^{-1}$ to $-30$ ms·month$^{-1}$.

The observed mean flow forcing in the 70-85 km region from a tropical station is reported to be $10-100$ ms·day$^{-1}$ [Hitchman et al., 1992]. Over extra tropical sites it is found that mean flow forcing was in the range $10-70$ ms·day$^{-1}$ in the mesospheric and lower-thermospheric regions [Reid and Vincent, 1987; Fritts and Yuan, 1989]. Over a mid latitude site, the zonal and meridional drag induced by the gravity waves with periods from 5 min to 8-10 hours were $51$ ms·day$^{-1}$ and $4$ ms·day$^{-1}$ during solstices and $-4.0$ ms·day$^{-1}$ and $7.4$ ms·day$^{-1}$ during equinoxes respectively [Nakamura et al., 1993]. Tsuda et al., [1990] using MU radar showed that the typical easterly
accelerations in the 70 -90 km height region ranged from 7 to 13 ms\(^{-1}\)day\(^{-1}\) and from -8 to -11 ms\(^{-1}\)day\(^{-1}\) in summer and winter respectively.

### 6.7.4.2 Forcing from Gravity Wave Towards MSAO

The mean flow acceleration calculated using the equation (6.12) is regarded as the estimated mean flow acceleration. This estimated mean flow acceleration due to gravity waves is compared with the observed acceleration calculated from the monthly mean zonal winds. Figures 6.8(a)-(l) show comparison of the mean flow acceleration calculated from monthly mean zonal winds (solid line) and that estimated (dashed line) using equation (6.12) for the westerly and easterly phases of six MSAO cycles listed in Table 6.2. In the first cycle (figure 6.8(a)), the observed mean flow acceleration is in the range \(-18\) to \(20\) ms\(^{-1}\)month\(^{-1}\) in the 82-88 km height region and the estimated mean flow acceleration due to gravity wave momentum flux divergence in this height region ranges from \(-5\) to \(9\) ms\(^{-1}\)month\(^{-1}\). Thus, the contribution of the gravity wave towards the westerly phase of MSAO ranges from \(~30\) to \(~50\)% in the 82-88 km height region. However, it is very interesting to note the similar trends in the observed and estimated acceleration in the 82-88 km height region.

At heights above 90 km the observed and estimated acceleration are in the opposite direction. From figure 6.8(b), it is seen that the observed mean flow acceleration in the easterly phase of MSAO is \(\sim-27\) ms\(^{-1}\)month\(^{-1}\) around 82 km while the estimated mean flow acceleration is \(\sim-9\) ms\(^{-1}\)month\(^{-1}\). Above 88 km, the estimated mean flow acceleration is slightly more than the observed mean flow acceleration. The contribution of gravity waves towards the mean flow acceleration is \(\sim30-40\)% in the 82-85 km height region. The contribution of gravity waves towards the westerly phase is found to be more than the easterly phase of the first MSAO cycle considered here. Figures 6.8(c) and (d) represent the westerly and easterly phases of the second MSAO cycle.
Figure 6.8 (a)-(l) Altitude profiles of observed (solid line) and estimated acceleration (dotted line) for six MSAO cycles during June 2004-May 2007. Refer Table 2.1 for details of MSAO cycles. Cycle number and easterly (E)/ westerly (W) phase of the MSAO (for e.g. 1W/1E) are given in each plot.
In this cycle during westerly phase the maximum contribution is at 88 km while in the easterly phase it is around 88 km. During both westerly and easterly phases of third MSAO cycle, the estimated mean flow acceleration is more than the observed mean flow acceleration above 82 km, which is clearly seen in figure 6.8(e) and (f). In this cycle, the estimated acceleration is either more than the observed acceleration or in the exactly opposite direction in the 82-98 km height region. The contribution of gravity waves is ~96% and ~1% at around 82 km in the westerly and easterly phases respectively. In the westerly phase of fourth MSAO cycle as seen in figure 6.8 (g), the estimated mean flow acceleration is slightly more in the 90-94 km height regions. In this phase the contribution of gravity waves varies from ~2% to 30% in the 82-88 km height region. From figure 6.8(h), the contribution of gravity waves towards the easterly phase of fourth MSAO cycle is almost 50% in the 82-94 km height region. In the fifth cycle the gravity wave contribution decreases from 60% to 1% in the 82-88 km height region as in figure 6.8(i). The easterly phase of fifth MSAO cycle is shown in figure 6.8(j). The gravity wave contribution in this phase is ~35 to 50% in the 82-88 km height region. The westerly and easterly phases of the sixth MSAO cycle are given in figures 6.8(k) and (l). In this cycle the estimated and the observed mean flow acceleration follows the same trend during the westerly phase (figure 6.8(k)). The contribution of gravity waves is found to be varying from 33% at 82 km to 1% at 88 km.

During the easterly phase of sixth MSAO cycle as shown in figure 6.8(l), large discrepancies are seen between the estimated and the observed mean flow acceleration at heights above 82 km. An interesting feature, which is evident in almost all the MSAO cycles, is that both the observed and estimated mean flow acceleration follows the same trend in 82-94 km height region (figures 6.8(a)-(l)). Also, it is evident from figures 6.8(a)-(l) that there is a considerable inter-annual variation in the mean flow acceleration during both easterly and westerly phases. Earlier studies by Garcia et al., [1997] ruled out the tidal driving as a plausible cause for the inter-annual variability of MSAO easterlies since the forcing of the diurnal tide was strongest at 100 km and it reduced from -4 ms\(^{-1}\)day\(^{-1}\) at 85 km to zero at 80 km. Studies using HRDI observations by Burrage et al., [1996] and modeling studies by Mengel et al., [1995] suggested that the filtering of small scale gravity waves could be another possible mechanism by which
lower stratospheric QBO could influence the MSAO. Another possibility for inter annual variation suggested by Sassi and Garcia [1997] was the significant contribution from intermediate-scale Kelvin waves and inertia gravity waves (of zonal wave numbers 5-25 and typical phase velocities ±30-60 ms\(^{-1}\)) to the forcing of easterly phase of MSAO when the stratospheric QBO was in westerly phase. However, a more comprehensive study is required to attribute the observed inter-annual variability of mean-flow acceleration to a certain atmospheric process.

A consolidated picture of the gravity wave forcing towards the westerly and easterly phases of MSAO is given in Table 6.3 along with errors in the percentage of contribution. It can be seen from Table 6.3 that the percentage of contribution during westerly phase varies from 20% to 60% while that during easterly phase varies from 30% to 70%. Thus, the gravity wave contribution is slightly more during the easterly phase than the westerly phase on an average during the period of study. The discrepancy between the estimated and the observed acceleration could be due to the contribution from planetary waves, inertia gravity waves and tides. These waves may be contributing in the opposite direction to that of gravity waves whenever the estimated acceleration exceeds the observed acceleration.

<table>
<thead>
<tr>
<th>Height(km)</th>
<th>% of contribution</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Westerly phase</td>
</tr>
<tr>
<td>82</td>
<td>50.8 ± 13.4</td>
</tr>
<tr>
<td>85</td>
<td>40.5 ± 7.2</td>
</tr>
<tr>
<td>88</td>
<td>13.8 ± 6.9</td>
</tr>
</tbody>
</table>

Table 6.3 Percentage of contribution of gravity waves (composite of all cycles) towards MSAO

Earlier modeling studies by Richter and Garcia [2006] have shown that during solstices, apart from small scale internal gravity waves, meridional advection contributes up to \(~9\) ms\(^{-1}\) day\(^{-1}\) during January and EP flux divergence from quasi two-day wave could contribute up to \(~8\) ms\(^{-1}\) day\(^{-1}\) of the easterly forcing of MSAO. The discrepancy could also be due to random errors in the measurements, which are found to be minimal in the Skiyymet meteor radar wind measurements. The accuracy in the radial wind measurement by Skiyymet meteor radar as given by Deepa et al., [2006b] is of the
order of 5% or better. The inter-annual variability of gravity wave contribution in both westerly and easterly phases of MSAO could be attributed to the selective filtering of gravity wave fluxes emanating from the troposphere by the lower level background winds as discussed by Eckerman and Vincent, [1994]. Thus, the present work quantified the forcing by mesoscale short period gravity waves towards the generation of different phases of MSAO over a low latitude site for the first time and also gave an excellent opportunity to understand the role of gravity wave forcing in controlling the MLT dynamics.

6.8 Summary

The present study discussed the measurement of gravity wave momentum fluxes in the MLT region employing a novel technique proposed by Hocking [2005] using meteor wind radar observations. Using three years of round the clock wind measurements from meteor wind radar in the MLT region over a low latitude site Trivandrum, momentum fluxes of mesoscale gravity waves of periods less than 2-3 hours were estimated for the first time employing this method. Unlike traditional dual beam method, this method makes use of meteor echoes to measure momentum fluxes in the MLT region using SKiYMET meteor radar. Altitude profiles of gravity wave momentum fluxes were oppositely directed to the mean wind, which is in close agreement with the earlier studies. The seasonal variation in the mesoscale short period gravity wave momentum fluxes showed a semi annual variation with equinoctial maxima and solstitial minima in contrast to mid and high latitudes, which showed annual variation.

Monthly mean zonal winds in the MLT region were used to investigate the characteristics of the MSAO. MSAO was prominently present in the 82-90 km height region and weak SAO with prominent easterly winds were present in the 91-98 km height region. There was no prominent SAO in the meridional winds in the entire height domain. Six MSAO cycles were chosen for the present study. Seasonal asymmetry in the strength of MSAO cycles is attributed to the modulation of the mesospheric zonal winds by the stratospheric QBO. Simultaneous observations of zonal winds in the stratospheric region using rocketsondes gave an excellent opportunity to compare the stratospheric SAO and MSAO. This comparison revealed an out of phase relation between the SSAO
and MSAO which were documented in the literature. This out of phase relation is explained on the basis of critical level filtering of the vertically propagating gravity waves and Kelvin waves by the stratospheric mean winds.

From the divergence of gravity wave momentum fluxes, the mean flow acceleration is estimated and compared with observed mean flow acceleration computed using the monthly mean zonal winds in the 82-94 km height region. Forcing of gravity waves towards the generation of westerly and easterly phases of six MSAO cycles were estimated, which is first of its kind over this tropical latitude. Gravity wave forcing towards the mean flow acceleration varied from cycle to cycle. This variability in the gravity wave forcing was explained on the basis of selective transmission of gravity waves by low-level background winds. From the present study, it was found that on an average, ~20-60% and ~30-70% of the forcing towards the westerly and easterly phases of MSAO respectively was from gravity waves which were in well agreement with earlier theoretical studies. The gravity wave forcing is found to be slightly more during the easterly phase than the westerly phase on an average during the period of study. The discrepancy between the estimated and the observed acceleration could be due to the contribution from planetary waves, inertia gravity waves and tides. Thus, the present study for the first time gave an opportunity to estimate gravity wave forcing towards the generation of MSAO, which is an important input for the modeling community.