CHAPTER -4

PLANETARY WAVES IN THE MLT REGION

4.1 Introduction

The present chapter discusses on the planetary waves in the MLT region by utilizing radar data from the low latitude stations Tirunelveli (8.7°N) and Pameungpeuk (7°S). The ground based radars have been providing useful information on the mean winds and wave activity in the MLT region. Planetary waves are global scale normal modes that are dominant in the MLT region. Signatures of these large scale wave motions are directly or indirectly observed in the dynamical field variables such as neutral wind and temperature. Generally, planetary waves with periods between 2 and 20 days are frequently observed in the MLT region. These atmospheric disturbances with resonance frequencies are associated with westward propagating Rossby normal modes. Another type of planetary waves which are confined over the equator, these waves are called equatorially trapped planetary waves. Equatorially trapped waves are classified into Kelvin waves and mixed-Rossby gravity waves and are trapped between ±15°N. These waves are believed to play a key role in forcing the equatorial QBO and SAO. Salby [1981a, b] interpreted that these wave disturbances are the response of the atmosphere to a forcing from below. It is important to note that these wave motions are sensitive to background wind circulation that in turn depends upon their phase speed [Forbes et al., 1995]. The propagation of the planetary waves into the MLT region is possible under suitable conditions [e.g. Vincent, 1990].

4.2 Planetary waves

This section presents some of the important results of earlier investigations on planetary normal modes, namely, the quasi 16-day wave, the 6.5 day wave and the 3.5 day wave. There have been several reports which focused on the planetary scale oscillations in
the mesosphere and lower thermosphere (MLT) region using various instruments and identified that these waves contribute significantly to the variability of atmospheric parameters in this region.

4.2.1 The quasi 16-day wave

The 16-day wave is a westward propagating wave with zonal wavenumber 1 and it has been identified as second symmetric Rossby (1,-4) mode [Salby, 1981a]. Though, it is traditional to refer the wave as quasi 16-day wave, the wave displays period between 12-20 days as predicted from theoretical concept [Salby, 1981a]. Williams and Avery [1992] measured the oscillations with periods between 12 and 19 days at Poker Flat (65°N, 147°W), Alaska using Mesosphere-Stratosphere-Troposphere (MST) radar data during the period 1984. In accordance with theoretical predictions, they found that the 16-day wave has maximum amplitude in the winter stratosphere. But, the interesting thing is, they observed significant wave amplitude at 85 km in summer period and provided an explanation for the presence of 16-day wave in the MLT during the summer period.

Forbes et al. [1995] performed numerical simulations on 16-day wave in January month. They confirmed and interpreted that this wave is a result of direct upward propagation into the MLT region. They also suggested that some leakage of these waves across the equator and into the summer mesopause region. Miyoshi [1999] examined the behaviour of 16-day wave in the MLT region using general circulation model. They found that inter-hemispheric penetration of the 16-day wave occurs near the mesopause region. Using 4 years of Meteor winds at Sheffield, Mitchell et al. [1999] studied the 16-day wave in the mesosphere and lower thermosphere. They observed that the largest 16-day wave amplitudes occur from January to mid-April, possibly, as a result of a smaller amplification during late boreal summer/autumn and a minimum amplification from late June to early July. Thus, the largest 16-day wave amplitudes generally occur in the winter
time and a secondary maximum is observed in the summer MLT [Luo et al., 2000; Espy et al., 1997; Mitchell, 1999].

The climatological studies on 16-day oscillations in the northern MLT reveals that strongest wave activity occurs during the winter solstices (January- March), which is believed to be the result of vertical propagation from lower levels [Forbes et al., 1995; Luo et al., 2002]. The 16-day wave in the winter time has largest amplitude in Northern hemisphere than in Southern hemisphere [e.g., Alexander and Shepherd, 2010]. Some of the important studies were made about the 16-day planetary wave are pointed here [e.g. Forbes et al., 1995; Miyoshi, 1999; Luo et al., 2002a; Jiang et al., 2005; Lima et al., 2006; Day and Mitchell, 2010, K.A. Day et al., 2011].

4.2.2 The quasi 6.5 day wave

A robust feature in the MLT region is ‘the quasi 6.5 day wave’, a quasi periodic wave with periods between 5 and 7 days [Talaat et al., 2001, 2002; Liu et al., 2004; Riggin et al., 2006]. It is believed that the 6.5 day wave in the mesosphere propagates westward with zonal wave number 1. Earlier studies have investigated the source and the relevant mechanism for the generation of mesospheric 6.5 day wave by model simulations [Meyer and Forbes, 1997; Liu et al., 2004; Riggin et al., 2006]. In recent decades, the ~6.5-d wave was identified by both ground based and satellite based observations [Wallace and Chang, 1969; Madden and Julian, 1972; Geisler and Dickinson, 1976; Wu et al., 1994; Kovalam et al., 1999; Talaat et al., 2001, 2002; Clark et al., 2002; Sridharan et al., 2003; Lieberman et al., 2003; Kishore et al., 2004; Lima et al., 2005; Riggin et al., 2006; Jiang et al., 2008]. This westward propagating 6.5 day wave features are strongly identified during equinoxes [Talaat et al., 2001, 2002; Lieberman et al., 2003; Kishore et al., 2004; Liu et al., 2004; Riggin et al., 2006; Jiang et al., 2008]. Sridharan et al. [2003] pointed that the phase speed of the 6.5 day wave is 65 ms\(^{-1}\) for zonal wave number 1 and
this wave generally can overcome the stratospheric quasi biennial oscillation wind speed and reach into the mesospheric altitudes.

A few radar observations were made to study the planetary scale oscillations in the equatorial mesosphere and lower thermosphere region. MF radar observations from Pontianak (0°N, 109°E) and Christmas Island (2°N, 157°W) revealed the presence of 6.5-day and 3.5-day waves [Kovalam et al., 1999]. This 6.5-day wave was identified as a manifestation of an unstable mode, while the 3.5-day is identified as an ultrafast Kelvin wave. Examination in the phase differences obtained from cross-spectra between the two stations show that the 6.5-day wave is westward propagating with zonal wavenumber 1, while the 3.5-day is eastward propagating with wavenumber 1. The evidence of the 5-day wave and 6.5-day wave reported from the MLT winds measured by the High Resolution Doppler Imager (HRDI) onboard Upper Atmosphere Research Satellite (UARS) [Wu et al., 1994; Talaat et al., 2001; Clark et al., 2002] found that this wave appear frequently near equinoxes mostly in tropical latitudes.

Earlier studies have reported that the behaviour of planetary scale 6.5 day wave shows variable nature due to the highly variable nature of middle atmospheric background winds and wave sources. The possible reason could be the background atmosphere influences the vertical propagating planetary waves from the troposphere to MLT region. The variability of MLT mean winds needs to be examined in order to explain the presence of planetary waves at these heights.

4.2.3 The quasi 3.5 day wave

Another interesting class of planetary scale waves is ‘equatorially trapped waves’ that are generated by deep cumulus convection in the tropical troposphere. One of the important types of Kelvin waves which propagate into the MLT region is ‘Ultrafast Kelvin waves’ of period 3-4 day. Earlier studies suggested that the ultrafast Kelvin waves are expected to be a driving force of MSAO.
A few studies were carried out to study the ultrafast Kelvin waves in the upper mesosphere using ground based and satellite observations [Lieberman and Riggin, 1997; Kovalam et al., 1999; Yoshida et al., 1999]. Liebermann and Riggin [1997] suggested that ultrafast Kelvin waves are important source of eastward momentum in the lower thermosphere and are likely ineffective in the region near 85 km. Riggin et al. [1997] recently investigated the vertical structure and propagation characteristics of ultra fast Kelvin waves using a campaign observation with Meteor Wind Radar (MWR) near Jakarta (6.4°S, 106.7°E) and an Medium Frequency (MF) radar in Christmas Island (2°N, 157°E). Comparing the wind observations between two sites, they have estimated the zonal momentum flux and eastward acceleration of ultra fast Kelvin waves. Sridharan et al. [2003] studied the characteristics of ultra fast Kelvin waves over Tirunelveli using MF radar observations in the mesopause region. They suggested the large amplitude wave events preferentially occur during the westward flow regimes of background wind.

The present work makes use of wind observation obtained from MF radars operated at Tirunelveli (8.7°N) and Pameungpeuk (7.5°S) stations. This study has utilized only two years of radar data, because of the lack of continuous wind observations. Hence, this chapter is limited to study the planetary scale waves in the MLT region and its response to zonal circulation. The present study mainly concern about ~16-d, ~6.5-d and ~3.5-d planetary wave and the results are discussed in the context of understanding of the behaviour of planetary scale waves in the northern and southern low latitude MLT region.
4.3 Planetary waves over Tirunelveli

Figure 4.1 describes the daily averaged zonal and meridional winds observed at 88 km of MLT region over Tirunelveli for the year 2005 and 2007. Time series of daily averaged zonal and meridional winds at 88 km for the year 2005 is shown in figure 4.1a. This figure shows a strong semiannual oscillation (SAO) in zonal winds and annual oscillation in meridional winds. The mesospheric semiannual oscillation is characterized by maximum westward winds near equinoxes and maximum eastward winds near solstices [Reed, 1966; Garcia et al., 1997]. It is believed that the mesospheric SAO are driven partly by equatorial waves and partly by gravity waves [Dunkerton, 1982; Lindzen, 1981; Richter and Garcia, 2006]. No prominent signature of SAO is found in the meridional winds instead it shows annual oscillation.

![Figure 4.1(a): Time series of daily averaged zonal and meridional winds at 88 km for the year 2005 over Tirunelveli.](image-url)
Figure 4.1b presents the same but for the year 2007. We can infer from figure 4.1, the signatures of mesospheric SAO are prominently observed in the zonal component and annual oscillation in the meridional component.

Time – altitude cross section of daily averaged zonal (left) and meridional (right) winds in the height range 80-98 km for the year 2005 and 2007 are shown in Figure 4.2. The zonal component of mesospheric winds at 2005 shows the dominance of eastward ($\sim 20 \text{ ms}^{-1}$) wind at solstices and westward ($\sim 30 \text{ ms}^{-1}$) wind at equinoxes. The altitude profile of meridional winds shows annual behaviour. The zonal component of mesospheric winds in 2007 shows strong eastward ($\sim 30 \text{ ms}^{-1}$) wind at solstices and westward ($\sim 60 \text{ ms}^{-1}$) wind at equinoxes. The mesospheric winds observed in 2007 are comparatively stronger than the winds observed during 2005 over Tirunelveli. Peculiar extended westward wind phase is observed in the mesospheric winds after July 2007 and this westward continues till the end of December 2007.
4.3.1 Planetary wave activity during 2005

The existence of planetary waves in the MLT can be effectively studied using wavelet analysis and are presented in Figure 4.3. Figure 4.3 describes the wavelet power spectra of hourly zonal (top plot) and meridional (bottom plot) wind at a specific height 88 km for the year 2005 over Tirunelveli. The quasi 16-day wave is observed strongly in the winter of January-February month for the year 2005. The wave features are weakly observed in summer. Evidence with earlier investigations, the 6.5 day wave is found largely in spring and fall equinoxes. The 6.5 day wave varies with the period between 5 and 8 days and observed in spring March-April month. Further, in fall equinox, the 6.5 day wave features are observed with slightly shifted periodicity and observed in September month. The presence of 6.5 day wave features is observed weakly with reduced wave amplitude during the summer months. In addition to quasi 16-d and 6.5-d, the 3.5-d wave features are observed most commonly in the mesospheric winds. The 3.5-d ultra fast Kelvin wave is strongly noticed in the summer June-July months of the year 2005. All the three wave features are observed with large amplitude in the zonal component than in the meridional component. The above planetary wave observations can be summarized as follows.

1. The quasi 16 day wave is more dominant in zonal wind than in meridional wind. The maximum wave amplitude is observed in winter and secondary maximum in summer.

2. Irrespective of seasons, the quasi 6.5 day wave is observed largely with maximum amplitude in spring and fall equinoxes and less reduced wave amplitude in summer months. These observed planetary wave features are extracted by applying band pass filtering analysis to the mesospheric winds.
Figure 4.2: Time-altitude cross section of daily averaged zonal (left panel) and meridional (right panel) winds for the years 2005 and 2007 over Tirunelveli.

Figure 4.3: Wavelet spectrum of horizontal winds at 88 km for the year 2005 over Tirunelveli.
Figure 4.4 describes the band pass filtered wave amplitude in zonal and meridional winds for the year 2005 over Tirunelveli. The solid and dotted line represents the zonal and meridional components respectively. In order to extract the planetary wave features, the hourly winds are subjected to band pass filtering analysis.

**Figure 4.4: Temporal variation of filtered wave amplitude in hourly zonal (solid line) and meridional (dotted line) winds for the year 2005 over Tirunelveli.**

The quasi 16-d wave is band passed between the periods 12 and 20 day; for 6.5 day wave, between 5.5 and 8 days; for 3.5 day wave, between 3 and 4 days. The filtered wind amplitude for 16-d wave show large amplitude in winter periods. The 6.5 day wave show maximum filtered amplitude in spring and fall equinoxes and minimum amplitude in summer. A signature of ultra fast Kelvin waves of amplitude $30 \text{ ms}^{-1}$ is observed strongly.
in June-July months of the year 2005. The filtered global wave modes ∼16-d, 6.5-d and 3.5-d are dominantly observed in the zonal wind component than in the meridional component.

**Interaction with background wind**

Figure 4.5 represents the temporal variation of 16-d wave amplitude for the height range 84-98 km (top plot) and mean zonal wind (bottom plot) for the year 2005 over Tirunelveli. The black solid line represents the zero mean zonal wind. The 16-d wave of amplitude > 24 ms⁻¹ is observed during the January-February of the year 2005. This winter 16-d wave amplitude is extensively observed up to 98 km. In addition to the winter 16-d wave, secondary maximum wave amplitude is observed in August (day no: 240) corresponding to the summer activity. The propagation of planetary scale waves in the middle atmosphere is mainly depends on the background wind condition. Temporal variation of 16-d wave amplitude associated with mean zonal wind structure reveals that large wave amplitude occurs near the zero zonal mean wind. This observed signature is contrast to the report by Luo et al., [2000]. They observed the stronger 16-d wave amplitude occurs when the background wind was eastward.

Time-altitude cross section of quasi 6.5 day zonal wave amplitude (top panel) in relation with background wind (bottom panel) for the year 2005 over Tirunelveli is shown in figure 4.6. Black solid line represents the zero mean zonal wind line. The 6.5-d wave amplitude is strongly observed in the month of April and October months. Mean zonal wind structure shows the presence of zero mean zonal wind line is found near the same (April and October) months. The enhancement of wave amplitude is noted when the zonal wind changes from westward to eastward. The observed 6.5-d wave of amplitude 24 ms⁻¹ near zero wind line propagates to up 98 km. In comparison with the observed equinox wave amplitude, a wave amplitude ∼21 ms⁻¹ is observed in July. This summer wave
amplitude observed at July is found near the zero wind line. The summer 6.5-d wave reaches up to 90 km. Notable 6.5-d wave amplitude in the MLT region suggests that these waves might propagate from the lower atmosphere.

Figure 4.7 represents the temporal variation of 3.5-d wave amplitude for the height range 84-98 km (top plot) and mean zonal wind (bottom plot) for the year 2005 over Tirunelveli. The black solid line indicates the zero mean zonal wind line. A signature of 3.5-d wave is observed strongly in the month of July of amplitude 30 ms\(^{-1}\) and reaches up to 92 km. The observed 3.5-d wave amplitude in the month of August propagates upward and reaches up to 98 km. During August, the background zonal wind is westward in nature. This indicates that the presence of westward wind in the MLT region permits the eastward propagating ultra fast Kelvin waves to propagate upward. In addition 3.5-d wave amplitude is noted in the month of November, associated with zero wind line. All the three planetary waves show maximum wave amplitude near the zero zonal wind line.

4.3.2 Planetary wave activity during 2007

The presence of planetary wave activity during the year 2007 is indicated by the wavelet power spectrum. Figure 4.8 describes the wavelet power spectra of hourly zonal and meridional winds at 88 km for the year 2007 over Tirunelveli. The planetary waves of periods \(~16\)-d, \(~6.5\)-d, \(~11\)-d and \(~3.5\)-d are observed in the mesospheric winds during the year 2007. The 16-d wave features are observed strongly in January-February and June months. The observed 16-d wave in winter month is global Rossby normal modes.

Distinct from the winter 16-d wave characteristics, strong wave amplitude of period 16-d is found in the summer (June-August) period. The observed significant \(~16\)-d wave features during summer. It reveals that the summer \(~16\)-d wave activity consist with the characteristics of long period slow Kelvin waves and are briefly discussed in the Chapter-3.
Figure 4.5: Time-altitude cross section of 16-d wave amplitude for the height range 84-98 km (top plot) and mean zonal wind (bottom plot) for the year 2005 over Tirunelveli. The black solid line represents zero mean zonal wind.

Figure 4.6: Time-altitude cross section of 6.5-d wave amplitude for the height range 84-98 km (top plot) and mean zonal wind (bottom plot) for the year 2005 over Tirunelveli.
In addition to 16-d normal mode, the waves with period 11-d, 6.5-d is also identified. The 11-d planetary wave is observed at the end of August. This wave is largely observed in the zonal component than in the meridional.

Wavelet analysis on 6.5-d wave shows that in the MLT region, the wave maximizes before and after the equinoxes and minimizes in summer. The 6.5d wave of maximum amplitude about 60 ms$^{-1}$ is strongly observed in both the before and after month of March (spring equinox). The 6.5d wave of amplitude 40 ms$^{-1}$ is observed in both the before and after month of September (fall equinox). Maximum 6.5-d wave amplitude is found in spring equinox than fall equinox. Weak 6.5-d wave amplitude is observed in June month. The observed 6.5-d wave features are consistent with the Liu et al. [2004]. Additionally, 4-d wave oscillation is observed at the end of August in both zonal and meridional wind component. The amplitude of 4-d wave is larger in zonal component than in meridional component. This 4-d wave might be an in-situ generated wave due to perturbation in the atmospheric field variables. An ultra fast Kelvin wave with period 3.5 day is noted in the month of August-November. The 3.5-d wave features are weakly observed in June.

Figure 4.9 shows the filtered wind amplitude of hourly zonal and meridional winds at 88 km for the year 2007 over Tirunelveli. The zonal and meridional components are represented by solid and dotted line respectively. For the 16-d wave, the horizontal winds are band passed between 12 and 20 day. Filtered 12-20d wave amplitude is observed in the January –February and June-august months, verifying with wavelet spectrum. The 16-d wave amplitude is larger in zonal component than in meridional. The 10-12 day filtered winds (~11-d wave) show maximum amplitude of about 10 ms$^{-1}$ in the month of August. The 11-d wave shows comparable amplitude in both zonal and meridional component.
Figure 4.7: Temporal variation of 3.5-d wave amplitude for the height range 84-98 km (top plot) and mean zonal wind (bottom plot) for the year 2005 over Tirunelveli.

Figure 4.8: Wavelet power spectra of hourly zonal (top plot) and meridional (bottom plot) winds at 88 km for the year 2007 over the low latitude station Tirunelveli.
Figure 4.9: The filtered wind amplitude of hourly zonal and meridional winds at 88 km for the year 2007 over Tirunelveli.

The filtered 6.5 d wind amplitude clearly evidences that the wave maximizes during before (February and August) and after (April and October) the equinoxes and minimum in equinoxes (March and September) and summers. Maximum filtered wind amplitude of about 20 ms$^{-1}$ is observed at before and after the spring equinoxes and reduced wave amplitude is found in before and after the fall equinoxes. The 3-4 day filtered wind shows maximum amplitude in June.

**Influence of background wind**

Figure 4.10 describes the temporal variation of ~16-d wave amplitude for the height range 84-98 km (top plot) and mean zonal wind (bottom plot) for the year 2007 over Tirunelveli. The zero zonal mean wind is represented by black solid line. Temporal variation of 16-d wave amplitude associated with background wind clearly represents the
characteristics and types of planetary wave. The 16-d wave is observed with maximum amplitude in January-February month. The observed 16-d wave amplitude in winter is associated with zero zonal wind. The enhancement of winter 16-d wave is observed when the background changes from eastward to westward. This signifies the observed 16-d wave in winter is a westward propagating Rossby wave. The amplitude of winter 16-d wave is reached up to 94 km. As discussed from Chapter 3, the long period slow Kelvin waves propagate from the lower atmosphere to mesospheric heights, because of existence of westward wind throughout the stratospheric region. Distinct from the year 2005, an extended period of westward wind is observed from July to December in the MLT region for the year 2007. The observed ~16-d wave during July–August shows strong wave amplitude of 24 m s\(^{-1}\). The presence of extended westward background condition allows the eastward propagating slow Kelvin waves to propagate upward. The summer ~16-d wave activity reaches up to 92 km.

Figure 4.11 represents the time–altitude cross section of 6.5-d wave amplitude in zonal component for the height range 84-98 km (top plot) and mean zonal wind (bottom plot) for the year 2007 over Tirunelveli. The black solid line represents the zero mean zonal wind. Temporal variation of 6.5-d wave amplitude clearly shows the strong wave amplitude in before and after the spring and fall equinoxes. The 6.5-d wave maximizes between the height region 84-88 during the months February & August (before) and May & October (after). At higher heights 90-96 km, the maximum 6.5-d wave amplitude is observed at fall equinox (September). The summer months show weak 6.5 d wave activity.

Once again, it may be recalled that the mean zonal wind the MLT region undergoes semiannual oscillation with westward flow in equinoxes and eastward flow in solstices. Earlier studies suggested that the planetary wave propagation depends on wave sources and background condition. As for as, we have separately studied the planetary
wave activity and its response with mean zonal circulation during 2005 and 2007. Earlier radar observations showed that mesospheric semiannual oscillation is modulated by stratospheric QBO [Burrage et al., 1996]. This modulation of mesospheric winds by stratospheric QBO is apparent only during SAO westward phase, which is considerable stronger when QBO winds are eastward than when they are westward. The stratospheric QBO shows similar phase structure during the years 2005 and 2007; this permits us to study the role of the variability of wave sources and influence of mesospheric winds. The mesospheric winds at 2007 shows extended westward phase and continues till the end of December. The reason for extended westward phase in the mesospheric winds needs to be studied in further detail.

The top panel of the figure 4.12 shows the monthly mean zonal wind at 88 km (line plot) and monthly mean values of Singapore radiosonde winds at 30 mb (bar plot). The panels plotted below the top panel show the time variation of the amplitude of ~16-d, ~6.5-d and ~3.5d waves in zonal wind at 88 km. From this figure, the second panel shows that the ~16-d wave is more active when the stratospheric QBO winds are eastward and it has smaller wave amplitude when the underlying QBO winds are westward. Strong 16-d wave amplitude of ~40 m/s in winter period and ~20 m/s in summer period is observed during the year 2005. The 16-d wave activity observed in 2007 show much reduced wave amplitude than wave activity during 2005.

During the year 2007, the observed ~16-d wave in both winter and summer shows comparable amplitude. The observed winter ~16-d wave amplitude consists with the characteristics of westward propagating planetary Rossby waves. The observed 16-d wave amplitude in summer monsoon consists with the characteristics of Kelvin waves.
Figure 4.10: Temporal variation of ~16-d wave amplitude for the height range 84-98 km (top plot) and mean zonal wind (bottom plot) for the year 2007 over Tirunelveli.

Figure 4.11: Temporal variation of ~6.5-d wave amplitude for the height range 84-98 km (top plot) and mean zonal wind (bottom plot) for the year 2007 over Tirunelveli.
Figure 4.12: Comparison of the time variation of monthly mean zonal wind at 88 km (line) and Singapore QBO winds at 30 mb (bar) with that of the variance of the ~16-d, ~6.5-d and ~3.5-d waves in zonal wind at 88 km for the years 2005 and 2007. Black (Red) color corresponds to the year 2005 (2007).
The third panel shows that the 6.5-d wave activity is observed to be larger with when the stratospheric and mesospheric winds are westward. The 6.5-d maximizes before and after the equinoxes irrespective of background wind condition. If the phase speed of the propagating wave is greater than the background wind speed then the wave could propagate into higher altitudes. Strong ultrafast Kelvin wave activity is observed during the transition period from westerly to easterly. The strong 3.5 day wave amplitude of maximum 30 m/s is observed during the summer months. Comparing the 3.5 day wave activity with stratospheric QBO winds shows that the 3.5-d wave independently propagates whether the QBO winds are eastward or westward. The reason for this independence have been reported by earlier studies that 3.5-d wave is an ultra-fast Kelvin wave with eastward phase speeds of 40-60 m/s and stratospheric QBO eastwards winds (nearly 15 m/s) are only half strong as QBO westward winds. Hence, the vertical propagation of ultra fast Kelvin wave is not affected by stratospheric and mesospheric winds. Earlier studies suggested that the reason for eastward phase of mesospheric SAO is not likely to be modulated by stratospheric QBO. Preferably, the 3.5-d wave energy appears during the westward phase of MSAO.

4.4 Planetary waves over Pameungpeuk

The present section presents the planetary wave signatures observed in the southern low latitude MLT region using Pameungpeuk MF radar data. Figure 4.13 describes the daily averaged zonal and meridional winds observed at 88 km of MLT region over Pameungpeuk for the year 2008 and 2009. Time series of daily averaged zonal and meridional winds at 88 km shows a strong semiannual oscillation (SAO) and annual oscillations. The semiannual oscillation in mesospheric winds are characterized by maximum westward near equinoxes and maximum eastward winds near solstices [Reed, 1966; Garcia et al., 1997].
Figure 4.13: Time series of daily averaged zonal and meridional winds at 88 km for the year 2008 and 2009 over Pameungpeuk.

Figure 4.14 describes the time-altitude cross section of monthly mean zonal and meridional winds from 2008 to 2009 over Pameungpeuk. The zonal mean structure shows alternating eastward and westward winds in the MLT region. It shows the presence of eastward winds in solstices and westward winds in equinoxes. In 2008, strong westward wind of about $\sim -40 \text{ m s}^{-1}$ is observed in March equinox and weak eastward wind of about $\sim 5 \text{ m s}^{-1}$ is observed during the summer period. During the year 2009, strong westward (of about $\sim -40 \text{ m s}^{-1}$) and eastward wind (of about 20 m s$^{-1}$) are observed. The mean zonal wind at 2009 winter period shows early onset of westward wind in the middle of January 2009 and continues throughout the winter. The signatures of early onset of westward wind in low latitude MLT region needs further detailed study. Strong eastward winds are observed in the summer months of 2009. Time –altitude cross section of mean meridional wind shows annual oscillation.
Figure 4.15 describes the wavelet power spectra of hourly zonal (top plot) and meridional (bottom plot) wind at a specific height 88 km from 2008 to 2009 over Pameungpeuk. Wavelet spectrum shows the presence of planetary waves with periods ~16-d and ~6.5-d. The quasi 16-day wave is observed strongly in the winter of January-February month for the year 2008 and the ~16-d wave features are weakly observed in summer. The ~16-d wave activity observed at winter 2009 is very weak with wave energy less than the summer wave activity. The observed suppression of ~16-d planetary wave during winter period is possibly can due to the influence of major stratospheric warming occurred in January 2009. Several studies suggested the reduced planetary wave activity in low latitude MLT region during the course of major warming. During 2009, sequence of 16-d wave amplitude is observed for the periods March-April, May-June and August-September months of 2009. This indicate ~16-d wave energies in 2009 are observed during the transition periods, winter-equinox and summer-equinox. The observed ~16-d wave energy during May-June and August-September months show much stronger activity. Evidence with earlier investigations, the 6.5 day wave is found largely in spring and fall equinoxes. The 6.5 day wave varies with the period between 5 and 8 days and observed in spring March-April month. Further, in fall equinox, the 6.5 day wave features are observed with slightly shifted periodicity and found the presence in September month. The presence of 6.5 day wave features is observed weakly with reduced wave amplitude during the summer months. All the three wave features are observed with large amplitude in the zonal component than in the meridional component. These observed planetary waves are extracted by applying band pass filtering analysis to the mesospheric winds.
Figure 4.14: Time-altitude cross section of monthly mean zonal (top) and meridional (meridional) winds from 2008 to 2009 over Pameungpeuk.

Figure 4.15: Wavelet spectrum of horizontal winds at 88 km from 2008 to 2009 over Pameungpeuk.
Figure 4.16 describes the band pass filtered wave amplitude in zonal and meridional winds for the year 2008 and 2009 over Pameungpeuk. The zonal and meridional components are represented by solid and dotted line respectively. In order to extract the planetary wave features, the hourly winds are subjected to the band pass filtering analysis. The quasi 16-d wave is band passed between the periods 12 and 20 day; 6.5 day wave, between 5 and 8 days.

![Temporal variation of filtered wind amplitude](image)

**Figure 4.16: Temporal variation of filtered wind amplitude in hourly zonal (solid line) and meridional (dotted line) winds for the year 2008 and 2009 over Pameungpeuk.**

The filtered wind amplitude for 16-d wave show large amplitude in winter periods of 2008. The filtered 6.5d wave amplitude is strongly observed with maximum amplitude.
in spring and fall equinox than summer. The filtered global wave modes ~16-d and 6.5-d are dominantly observed in the zonal wind component than in the meridional component.

Figure 4.17 represents the temporal variation of 16-d wave amplitude for the height range 84-98 km (top plot) and mean zonal wind (bottom plot) from 2008 to 2009 over Pameungpeuk. The black solid line represents the zero mean zonal wind line. A 16-d wave of amplitude 27m/s is observed at the end of February during 2008. No indication of strong ~16-d wave amplitude in winter period during 2009 winter period.

Figure 4.17: Temporal variation of 16-d wave amplitude for the height range 84-98 km (top plot) and mean zonal wind (bottom plot) from 2008 to 2009 over Pameungpeuk. The black solid line represents the zero mean zonal wind line.
Instead, a strong ~16-d wave amplitude is observed at the summer-equinox transition period associated near with zero mean zonal wind line. The 16-d wave activity is suppressed during 2009 winter. The reason for suppression of 16-d wave activity might be due to the observed major stratospheric warming in January 2009.

Figure 4.18: Comparison of the time variation of monthly mean zonal wind at 88 km (line) and Singapore QBO winds at 30 mb (bar) with that of the variance of the ~16-d and ~6.5-d waves in zonal wind at 88 km from 2008 to 2009 over Pameungpeuk.
The top panel of the figure 4.18 shows the monthly mean zonal wind at 88 km over Pameungpeuk (line plot) and monthly mean values of singapore radiosonde winds at 30 mb (bar plot). The panels plotted below the top panel show the time variation of the amplitude of ~16-d, ~6.5-d and ~3.5d waves in zonal wind at 88 km.

Earlier radar observations stated that the mesospheric SAO is modulated by stratospheric QBO winds. This modulation of mesospheric winds by stratospheric QBO is apparent only during SAO westward phase, which is considerable stronger when QBO winds are eastward than when they are westward. From figure 4.18, we can see a strong mesospheric SAO modulation when the stratospheric QBO winds are eastward. The mesospheric SAO is strongly modulated by the stratospheric QBO winds during the year 2008 and 2009 [Burrage et al., 1996]. From this figure, the second panel shows that the ~16-d wave is more active when the mesospheric SAO winds are eastward and near zero zonal wind line. The strong ~16-d wave activity is observed strongly in both stratospheric QBO east and west phase. Active ~16-d wave activity is observed even when the stratospheric QBO winds are in eastward phase. Early onset of westward wind in the winter period might be the reason for suppression of ~16-d wave activity in 2009 winter. During the suppression of ~16-d wave activity, the enhancement of ~6.5-d wave activity is also noted.

### 4.5 Discussion

The present work describes the planetary scale waves in the MLT region and its response to zonal circulation using MF radars operated at Tirunelveli (8.7°N) and Pameungpeuk (7.5°S). The present study mainly concerns about planetary waves with periods ~16-d, ~6.5d and ~3.5 day and the results are discussed in the context of understanding of planetary scale waves in the northern and southern low latitude MLT region. The mesospheric winds over Tirunelveli show semiannual oscillation (SAO) in
zonal winds and annual oscillation in meridional winds. Mesospheric semiannual oscillation is characterized by maximum westward winds near equinoxes and eastward winds near solstices. Planetary waves with periods ~16-d, ~6.5-d and ~3.5-d are predominantly observed in the zonal component over Tirunelveli. The wave activity in zonal is comparatively larger than meridional winds. The maximum ~16-d wave amplitude is observed during winter and secondary maximum in summer period. Large 16-d wave amplitude is noted when the mesospheric wind changes from eastward to westward. The 6.5-d wave amplitude maximizes at equinoxes and minimizes in summer. The 6.5-d wave activity is largely observed when the stratospheric and mesospheric winds are westward. All three ~16-d, ~6.5-d and ~3.5-d wave modes show maximum wave amplitude near the zero zonal wind line.

The extended westward phase of mesospheric winds is observed from July to December 2007. The presence of extended westward phase allows the propagation of long period Kelvin waves of periods (~16-d and ~23-d) from lower atmosphere into the mesospheric altitude.

In addition, we have discussed the planetary wave activity in the southern low latitude MLT using MF radar data from 2008 to 2009 over Pameungpeuk. The MLT winds over Pameungpeuk also show semiannual variation in zonal component and annual oscillation in meridional. Notable signature of modulation of mesospheric SAO by stratospheric QBO winds are observed over Pameungpeuk during the year 2008 and 2009. The 16-d wave activity at Pameungpeuk is more active when the mesospheric SAO winds are eastward and near zero zonal wind line. The strong ~16-d wave amplitude at 88 km is observed at both QBO east and west phase. More analysis needs to be carried out to study the cause for suppression of ~16-d wave and enhancement of 6.5-d wave during the 2009 winter over Pameungpeuk. Sudden major warming occurred at January 2009 in the polar
stratosphere might be the reason for the suppression of ~16-d wave activity [Day et al., 2011].

Day et al., [2011] studied the westward propagating s=1, 16 day planetary wave in the stratosphere, mesosphere and lower thermosphere using Aura MLS temperature observations during the period from August 2004 to December 2010 over the latitude region 75°N to 75°S. They suggested that wave amplitudes are closely related to mean zonal winds and are largest in regions of strongest eastward flow. They do not observe a significant QBO modulation of the 16-day wave amplitude in the polar summer-time MLT. They also suggested that wave amplitudes were also observed to be suppressed during the major sudden stratospheric warming events of the Northern Hemisphere winters of 2006 and 2009.

With the aid of six ground based radar systems located in equatorial and midlatitude sites Platteville (40.18°N, 104.7°W), Yamagawa (31.2°N, 130.6°E), Wuhan (30.5°N, 114.3°E), Maui (20.75°N, 156.43°W), Tirunelveli (8.67°N, 77.82°E), and Adelaide (35°S, 138°E), Jiang et al., [2008] analyzed the presence of mesospheric 6.5 day wave from hourly winds during April-May 2003. They compared the global distribution of the observed 6.5 day wave with the theoretical structure. In addition, they investigated the important wave characteristics of the mesospheric 6.5 day wave event like wave period, vertical structure, propagation direction, relationship with background wind and zonal wave number. They summarized their results as: 1. the latitudinal structure of the mesospheric 6.5-day wave during April–May 2003 is basically in agreement with the theoretical Rossby mode (s, n) = (1, -2), although the wave amplitude of zonal wind peaked at the subequatorial latitude of Northern Hemisphere but not at the theoretical place, equatorial region; (2) the main wave periods and the altitude distribution of large amplitude of this wave event varied with latitude; (3) the downward propagating wave
phases indicated that this wave event originated in the lower atmosphere and propagated upward to the upper region.

*Sridharan et al.,* [2006] studied the characteristics of 5-8 day waves in the mesosphere and lower thermosphere over the Indonesian Regions, Kototabang (0.2°S, 100.3°E), Pontianak (0°, 109.3°E) and Pameungpeuk (7.5°S, 107.5°E). They found that the wave activity is larger in zonal wind than in meridional wind during the year 2003 and the wave activity maximizes before and after northern hemispheric spring equinox. In the year of 2004, the wave activity in zonal wind is larger during June-August 2004. The phase of the wave over Pontianak leads that over Kototobang indicating the wave is westward propagating with zonal wavenumber 1. They suggested that the wave period ranges from 6.3 to 7.0 days over the equatorial sites Kototobang and Pontianak whereas, over the southern hemispheric site, Pameungpeuk, it is in the range 6.2-6.4 days and also they found the three stations show similar amplitude and phase structure.

Using High resolution Doppler imager observations, *Lieberman and Riggin* [1997] examined the Kelvin wave features in the equatorial mesosphere and lower thermospheric zonal winds at solstice. They observed eastward propagating signatures with periods near 3 and 5 days of zonal wave number 1, 2 and 3. These wave structures are coherent in latitude and altitude. It maximizes near or on the equator. The phase structure at the mesospheric altitudes move downward in time which implies, these equatorial waves are forced from below. In addition, they made Eliassen-Palm flux analysis, to understand the contribution of eastward momentum flux by 3 and 5 day waves in the equatorial mesosphere and lower thermosphere.

They observed a broad peak near 5-7 days. The 6.5 day wave is observed as an equinoctial phenomenon when background wind is westward. The wave activity is strongly observed during April/May and September/October months which clearly explicit semiannual oscillation behaviour. The 6.5 day is strong in the zonal wind component and the wave activity is maximizes during the weak quasi biennial oscillation year and also found the interannual variability.

Using wind measurements over Pontianak (0°N, 109°E) and Christmas Island (2°N, 157°W), Kovalam et al., [1999] studied the zonal structure of the planetary scale waves in the mesosphere and lower thermosphere region. They utilized zonal and meridional wind observations from November 1995 to 1997. For Christmas Island, the analysis made for 8 years from January 1990 to December 1997. The amplitude and phase variation of these long period oscillations are obtained by power spectral technique. Zonal spectra show prominent oscillations with periods near 3.5 day and 6.5 day. Their results showed that strong 6.5 day waves during the period April to September. They found that the 6.5 day wave is westward propagating wave with zonal wave number 1 while the 3.5 day wave is eastward propagating with wave number 1. Further, they identified that the 6.5 day is manifestation of an unstable mode, whilst, the 3.5 day wave is an ultra fast Kelvin wave. Also, they inferred significant longitudinal variations in the amplitude and momentum fluxes of 3.5 day wave, amplitudes were larger in Asian than in Central Pacific.

Tsuda et al., [2002] analyzed the long term variations of the wind velocity variance of ultra fast Kelvin waves (3.0-3.8d) and gravity waves in the equatorial mesosphere and lower thermosphere using Meteor wind radar observations at Jakarta (6°S, 107°E) from November 1992 to June 1998, as well as two MF radars at Christmas Island (2°N, 157°W) and Pontianak (0.03°N, 109°E) from January 1996 to July 1997. The long term variations of the Ultra fast Kelvin waves showed enhancements twice a year in 1993-1995, mostly
coinciding the westward wind phase of MSAO or the transition period of MSAO from eastward to westward wind. The wave activity is weaker in 1996-1997.

*Talaat et al.,* [2001] presents the global and seasonal analysis of the 6.5 day wave in High Resolution Doppler Imager day time mesospheric horizontal winds, temperature and atomic oxygen at 95 km. They found the horizontal structures of all these atmospheric variables are similar to the gravest symmetric Rossby wave (1,1) mode with wave number 1. The seasonal and spatial structures of 6.5 day clearly displays the modification by background zonal mean wind and the vertical structure indicates it is an internal Rossby wave.

*Buriti et al.,* [2008] observed mesospheric winds over Cariri (7.4°S) with meteor radar during the period of from July 2004 to June 2005. It shows clear semi-annual oscillation in mesospheric zonal mean wind which maximizes mainly at 82 km with decreasing amplitude with height. Maximum westward wind occurred in March and September. The meridional wind show clear annual variation maximizing in December.

*Sridharan et al.,* [2003] studied the possible influence of stratospheric quasi biennial oscillation on the vertical propagation of planetary scale waves to the MLT region by using hourly zonal and meridional winds at 86 km over Tirunelveli (8.7°N, 77.8°E) over a period of five years from 1993 to 1997. The radiosonde winds at Singapore were used to identify the phase of the stratospheric QBO at 30 hPa. They suggested that the interannual variability of the planetary waves is associated with direction of stratospheric QBO winds.

*Kishore et al.,* [2006] studied the planetary wave activities in the stratosphere and lower mesosphere by analyzing Rayleigh lidar temperature data over Gadanki (13.5°N, 79.2°E) during the two campaign periods 1999 and 2000. Periodogram and wavelet analysis indicated the presence of planetary waves with periodicities 3.5 day (Rossby-
gravity wave); 6.5 day (fast Kelvin wave) and 16 day (Slow Kelvin wave) are dominant in the low latitude middle atmosphere.

Tsuda et al., [1999] studied the equatorial atmospheric dynamics using Radars and radiosonde in the mesosphere and lower thermosphere (MLT) region. Meteor Radar located at Jakarta (6.4°S, 106.7°E) from November 1992 and Medium frequency radar in Pontianak (0.03°N, 109.3°E) from November 1995 utilized in this study. In addition to radar observations, they conducted Campaign observations with a balloon borne radiosonde in LAPAN observatories in Watukoesk (7.6°S, 112.7°E), Bandung (6.9°S, 107.6°E) and Pontianak since February 1990. First, they discussed the long term behaviour of zonal wind at 70-100 km using Jakarta MWR data during November 1992 and October 1997. They found the domination of Mesospheric Semi Annual Oscillation (MSAO) in the equatorial MLT region whose westward winds were much larger in March–April than in September–October. Moreover, the maximum amplitudes of MSAO showed a clear biennial periodicity. Also, they discussed the characteristics of ultra fast Kelvin waves having periods of 3-4 days. From the correlative study between the Jakarta, MWR and MF radars at Pontianak and Christmas Island, they indicated the ultra fast Kelvin wave propagates eastward at a zonal wavenumber 1. Further, they analyzed the long term behaviour of the 3-4 ultra fast Kelvin waves in Jakarta; the wave activity is characterized by strong enhancements twice a year, having a large value in the westward winds of MSAO.

Liu et al., [2004] studied the robust features of planetary scale waves with periods 6.5 days in the mesosphere and lower thermosphere region with prominent seasonal variability as revealed by ground based and satellite observations. The 6.5 day wave and its seasonal variability are well produced in NCAR TIME-GCM (National Center for Atmospheric Research –Thermosphere ionosphere mesosphere electrodynamics general
circulation model. The wavelet analysis of the model has shown that the wave maximizes before and after the equinoxes and minimizes at solstices. The wave amplitude at the equinoxes is smaller than the peaks before and after but still larger than the wave amplitudes at solstices. They studied the characteristics of this 6.5 day wave and seasonal variability in detail. They found that the wave source, mean wind structure, instability and the critical layers of the wave all can affect the wave response in the MLT region and strongly depend on season.

Talaat et al., [2002] studied the westward propagating 6.5 day wave with zonal wave number 1 using United Kingdom Meteorological Office (UKMO) data in the stratosphere and UARS/HRDI measurements of horizontal winds and temperature in the mesosphere and lower thermosphere. They observed two wave events, before and after the equinox at low latitudes in both UKMO and HRDI data; the wave is prominent near equinox. They analyzed the amplitude growth and phase decrease with altitude of the zonal wind 6.5 day wave. From the analysis, they suggested that the 6.5 day is propagating from the stratosphere to the MLT region. Further analysis of UKMO data, the presence of 10-day with wavenumber 1 and 4-day with wavenumber 2 were identified.