Short period oscillations in mesosphere

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Long sequences of the hourly average zonal and meridional wind components obtained by ME spaced antenna radars at Davis (69°S, 87°E), Buckland Park (34°S, 138°E) and Christmas Island (2°N, 157°W) are spectrally analyzed to study the short period oscillations in mesospheric winds. Data lengths covering a minimum of four years at each of the stations, five altitudes used for averaging (84-92 km) and the windows of 10, 20 and 40 days used in estimating power spectra give high reliability and spectral resolution. Apart from the tidal components at 24, 12, 8 and 6 h there are oscillations with periods ranging between 4.8 h and 12 h. Moving power spectra are obtained to study the seasonal dependence of the short periods smaller than 12 h. Oscillations. The wave activity is strongest during June solstice and weakest during equinoxes at each of the locations. The presence of similar features at high, mid and low latitudes indicates the global nature of such oscillations.

The seasonal dependence of the wave activity is in agreement with the recently reported observations of waves with periods between 7.5 and 10.5 h seen in the meteor radar data at south pole. Oscillations with periods of 4.9-5.2 h and 7.2-7.5 h are also seen.

I Introduction

Neutral atmospheric parameters like wind and temperature show a number of oscillations and wave-like motions superimposed on the general atmospheric circulation. These are classified, in terms of restoring forces, into (i) internal gravity waves, arising due to the stratification or buoyancy of the atmosphere with periods ranging from a few minutes (Brunt-Vaisala period) to the inertial period and (ii) Rossby or planetary waves, arising due to the variation of Coriolis force with latitude. Planetary waves are large-scale waves and periods near 2, 5, 10 and 16 days have been identified in the atmosphere. The inertia-gravity waves arise due to the combined stratification and Coriolis effects. The tides are the response of the atmosphere to some forcing like the lunar gravitational force with a periodicity of 12.4 h or to solar heating (fundamental period of 24 h with harmonics of 12 and 8 h).

In the absence of any forcing to an isothermal and dissipativeless atmosphere the solutions to the linearized equations governing the atmospheric motions are known as normal modes or free oscillations. Atmospheric free oscillations can take the form of gravitational modes, Rossby modes (for example the 5-d and 16-d waves), mixed Rossby-gravity (2-d wave) or Kelvin modes (33-h wave). The gravitational waves are usually referred to as Lamb waves and used to distinguish them from the longer period waves. However, the real atmosphere is non-isothermal and dissipative and, therefore, the response will be affected. Lindzen and Blake examined the effects of non-isothermality and dissipative nature of atmosphere using a one-dimensional model. The positive temperature gradient above ~90 km leads to internal wave behaviour, upward energy propagation and energy leakage from lower heights which leads to finite life time for Lamb waves. It was shown by them that the surface friction reduces and broadens the response and limits the lifetime of Lamb waves to ~4 days for wave periods between about 7 and 10 h.

Due to the large growth, relatively small oscillations in troposphere could achieve significant amplitudes in thermosphere (ionosphere). Below about 100 km, the vertical structure of Lamb waves is almost identical in both dissipative and dissipationless atmospheres. At greater heights both amplitude and phase approach constants in a characteristic manner of internal gravity waves.

The mesosphere-lower thermosphere (MLT) region is subjected to forcing by solar radiation absorption, Joule heating, particle precipitation and gravity wave momentum deposition. Meyer and Forbes studied the spectral response of this region based on numerical
The seasonal changes in the background atmosphere produced minimal changes in the spectral response, as the phase speeds of the short period waves are quite large. For symmetric forcing case, the zonal and meridional components of the wave for zonal wave number 1 maximize in the polar region in lower thermosphere (125-130 km). For zonal wave numbers 2 and 3, the largest response is seen at the equator for zonal and at mid-latitudes for meridional components and maximizes above 250 km. For asymmetric forcing, largest horizontal velocities are seen in the polar region near 125 km for zonal wave number 1. For zonal wave numbers 2 and 3, zonal wind maximizes at mid-latitudes above 250 km. Maxima at equator and mid-latitudes above 250 km are seen. Thus, both for the symmetric and asymmetric forcings the largest horizontal velocities are seen in the polar regions near 125 km for zonal wave number 1.

Meyer and Forbes\(^2\) also studied the response for heat sources located at 80, 90, 100 and 110 km. The period of the maximum response varied slightly with the location of the source. Peak response was seen at 11-h period for source at 80, 90 and 100 km and at 12 h for source at 110 km. However, the shape of the response is broader for source at 110 km and becomes narrower for source located at lower altitudes.

There is evidence that Lamb waves in substantial amplitude exist in the lower thermosphere. Hernandez \textit{et al.}\(^3\) observed a 10.1 h westward propagating wave over south pole from wind observations using optical spectrometer (-88 km) along eight azimuths. Wind observations by MF radar at Scott Base also indicated 10.1 h and 12 h oscillations. The observed phase propagation indicated the oscillation, about 8 m/s in amplitude, to have zonal wave number 1 and propagating westward and attributed to Lamb waves of planetary scale. Hernandez \textit{et al.}\(^4\) reported oscillations of 10 and 12.2 h with amplitudes of 5.5 and 6.1 m/s, respectively, from observations made during 1992. Reisin and Scheer\(^5\) reported a number of oscillations in temperature from airglow observations using OH (88 km) and \(O_2\) emissions with periods ranging between 10 and 14 h at locations 32\(^\circ\)S and 37\(^\circ\)N. Hernandez \textit{et al.}\(^6\) observed westward propagating waves with periods 9.9, 10.4 and 10.9 h and amplitudes 5-7 m/s by simultaneous meteor radar and optical observations during June 1995. Forbes \textit{et al.}\(^7\) have reported large oscillations with a period of 12 h from meteor radar wind data at 95 km measured at south pole. Meyer and Forbes\(^2\) attributed this to a normal mode, based on the results of the numerical simulation studies of the response. Portnygin \textit{et al.}\(^8\) reported the existence of 7-11 h oscillations from a year of meteor radar data near 95 km over south pole.
which appear to be Lamb waves. Due to the data length of 50 h used in estimating the spectra, the resolution was limited (about ± 2 h for 10 h and ± 1 h for 6 h). In a recent paper Forbes et al. report oscillations of ± 5–15 m/s with periods between 7.5 and 10.5 h, propagating to west with zonal wave number 1. The results were obtained from meteor radar data near south pole along the four meridians. The wave events usually last for 2–3 days and often the period shifts from one event evolving to another. The oscillations were interpreted as gravitational normal modes (Lamb waves). The second symmetric mode with period near 8.6 h and the first asymmetric mode with period 10.4 h appeared to dominate. Portnyagin et al. have further examined the meteor radar data at south pole from January 1995 to January 1996 in the lower thermosphere (95±5 km), employing both the periodogram (FFT) and S-transform techniques. They observed characteristic periods uniformly spaced between 7 h and 12 h, all propagating westward with zonal wave number 1. During winter season, periods less than 12 h are most intensive, while during summer 12 h period dominates. Lamb waves and internal-gravity waves propagation, non-linear interaction of the short period waves and the excitation in situ of short period waves were considered as possible processes responsible for the observed wind oscillations in the lower thermosphere over south pole.

The atmospheric physics group at the University of Adelaide in south Australia has been measuring mesospheric winds on a regular basis at few locations at different latitudes. The MF spaced antenna technique gives continuous wind observations in the altitude region 78-98 km at every 2 km interval of altitudes. Mean power spectra and moving power spectra of the zonal and meridional wind components in the region 84-92 km are obtained from data lengths covering a minimum of four years at each of the three stations. Periods of oscillations in the mesosphere have been identified over equatorial, mid-latitude and high latitude stations of Christmas Island, Buckland Park near Adelaide and Davis. The mean spectra based on few years of data at five altitudes provide spectral estimates with high reliability and resolution. Results of the oscillations with periods shorter than that of the semidiurnal oscillations are presented in this paper.

2 Data and methods of analyses

The MF radars used in the present study are identical and operate at 1.98 MHz (1.94 MHz at Davis) in spaced antenna mode. The radars located at Christmas Island (2°N, 157°W), Buckland Park (34°S, 138°E) and Davis (69°S, 78°E) represent the equatorial, mid-latitude and high-latitude regions, respectively. Raw data are analyzed in real time using the correlation analysis. Observations are recorded covering the altitude region of 60-98 km at 2 km intervals every two minutes. Hourly average zonal and meridional components of winds are processed offline and form the basis of the present study. The data cover the years 1990-97 for Christmas Island, 1990-92 and 1993-97 for Buckland Park and 1994-98 for Davis. The altitude range of 78-98 km provides continuous observations. However, we have selected data for 84-92 km which have maximum samples (of 2 minutes) in the hourly average values. At these altitude ranges data breaks are rare and linear interpolation method was used to fill any short gap in the time series.

The spectral estimates for the zonal and meridional winds are based on mean spectra. The data series are divided into segments of 20 days (480 points) and overlapped by 50% in order to minimize the variance associated with each spectral estimate. Data segments are windowed using a Welch function before estimating power spectra from the FFT technique. For the Welch method (modified Bartlett procedure) the spectrum window is proportional to the squared magnitude of the Fourier transform of the window, so that spectrum estimate is always non-negative. Also the width of the main lobe is broader compared to rectangular, Hann or Hamming windows. Mean spectra computed at five heights (84–92 km) were then averaged together to improve further the spectral estimates. Since the radar pulse length is about 4 km, spectra from adjacent heights are not completely independent. However, the total number of data segments used in estimating mean spectra are sufficiently large (more than 500), and the number of degrees of freedom associated with each spectral estimate, taken as half of the total number of data segments used, is very high. Confidence limits at 95% level are less than 1 and indicated in the spectra shown in the figures that follow. Power spectra were also estimated using a window of 10 days (240 points) and 40 days (960 points) which give better temporal estimate and resolution, respectively.

To study the temporal behaviour of the waves, moving power spectra are obtained. Power spectra are computed for a data window of 10 days and then the window shifted by a day and power spectra
re calculated. The procedure allows one to study the spectral behaviour with time. The moving power spectra at the five heights thus obtained are averaged. For further improving the significance level, average of moving power spectra is computed from different years of data. Moving power spectra were also computed with a data window of 40 days for a better spectral resolution.

3 Results

3.1 Mean power spectra

The annual average mean spectra of the zonal and meridional winds for Davis and Christmas Island estimated using a window of 20 days are shown in Fig. 1. The spectral resolution can identify peaks separated by 0.1 h at 5 h and by 0.4 h at 10 h. Zonal spectra are characterized by significant peaks at 24, 12, 8, 6 and 4.8 h at both the stations. There is an indication of a small peak at 4 h also. However, there is a difference in the magnitude of semidiurnal component relative to other tidal components. It is the strongest spectral component at Davis, while at Christmas Island the diurnal and semidiurnal components are of comparable magnitude. The mean spectra for the meridional component of winds show prominent peaks at 48, 24, 12, 8 and 6 h at both the locations. There are again indications of peaks at 4.8 and 4 h. There is a smaller but distinct peak at 16 h also at Christmas Island. Once again the semidiurnal peak is much stronger than the diurnal peak at Davis. Another feature to note is that the 24 h and 12 h peaks are sharper at Davis than at Christmas Island. The annual average mean spectra for the zonal and meridional winds for Buckland Park are shown in Fig. 2. There are peaks at 24, 12, 8 and 6 h in both the zonal and meridional wind components. The

Fig. 1—Frequency spectra of hourly averaged (a) zonal and (b) meridional winds averaged between 84 and 92 km at Christmas Island for the period January 1990-December 1997 (solid line) and at Davis for the period April 1994-June 1998 (dashed line) [95% confidence limits are indicated; PSD = Power Spectral Density.]
meridional component shows peak at 48 h also. There are indications of weaker peaks at 10, 4.8 and 4 h. The seasonal mean zonal and meridional spectra for Davis and Christmas Island during June solstices obtained using a window of 20 days are shown in Fig. 3. The spectra for Christmas Island show, in

![Graph](image)

**Fig. 2**—Frequency spectra of hourly averaged zonal (solid line) and meridional winds (dashed line) averaged between 84 and 92 km at Buckland Park (Adelaide) for the periods 1990-92 and 1993-97 [95% confidence limits are indicated].

![Graph](image)

**Fig. 3**—Frequency spectra of hourly averaged (a) zonal and (b) meridional winds averaged between 84 and 92 km at Christmas Island for the June solstices of the years 1996-97 (solid line) and at Davis for the June solstices of the years 1994-98 (dashed line) [95% confidence limits are indicated].
addition to the prominent tidal components (48, 24, 12, 8 and 6 h), small peaks or indication of a peak at 4.8, 5.5, 9 and 10.4 h for zonal component and at 5.2, 6.8-7.1 and 10.4 h for meridional component. The spectra for Davis show small peaks at 4.8, 6.2, 7.2, 8.8 and 9.8 h for the zonal component and at 4.8, 5.2, 8.7 and 10 h for the meridional component of winds.

3.2 Seasonal dependence

The seasonal dependence of the wave activity in the zonal and meridional wind components is studied from the average moving power spectra with a window of 10 days and averaged over the five altitudes of 84-92 km. The results are presented in the form of contours of power spectral density on a grid of the day of the year and frequency. To depict the behaviour of waves with periods shorter than that of the semidiurnal component, frequency range between 2.2 and 6.2 cycles/day is chosen. This covers the wave periods between 10.9 and 3.9 h. The plots for the zonal and meridional winds over Davis are shown in Fig. 4. For the zonal component the wave activity is high for waves with periods between 7.5 and 11 h and seen almost throughout the year. There are some periods, especially during equinoctial months, when oscillations are not seen. Oscillations with periods of 7.0-7.5 h are seen during the months of May-June and December-January only. Waves with periods between 4.8 and less than 6 h are seen as isolated events during June and December. For the meridional component of

![Zonal Winds](image1)

![Meridional Winds](image2)

Fig. 4—Annual-average moving-window power spectra of zonal and meridional winds at Davis for the period April 1994-June 1998 [A 10-day window is used. The bar indicates spectral density in m·s⁻¹·Hz⁻¹.]
wind, similar results are noted. The wave activity is maximum during June solstices with periods right from 6 h onwards and minimum during equinoxes. Contours also show the presence of the waves with different periods that appear at different times and are often changing during the course of time.

The seasonal dependence of the wave activity in the zonal and meridional wind components at Buckland Park (Adelaide) is shown in Fig. 5. Spectral density is very high for the 8 h period, which is present throughout the year in both components. There are oscillations with periods between 8 and 11 h with maximum power during solstices and minimum during equinoxes barring the strong activity noticed during September. The oscillations with periods less than 8 h are seen only during June and December solstices. Oscillations with periods less than 6 h are sporadic in nature and seen during June solstices. The results of the average moving power spectra for Christmas Island for the zonal and meridional components are shown in Fig. 6. The scale of the contour values is different in this case. The 8 h oscillation is seen prominently throughout the year. The 6 h component is also noticed except the equinoctial months. There are some instances of wave activity with periods between 6 and 8 h, especially, in the meridional component during solstices. The waves with periods between 8 and 11 h are more frequently observed.

Moving power spectra were also obtained using a window of 40 days for higher spectral resolution. The results for the zonal and meridional winds over Davis

Fig. 5—Same as Fig. 4, but for Buckland Park (Adelaide) for the period January 1990-December 1992 and January 1993-December 1997
are plotted in Fig. 7. The frequency range of 2.0-5.0 cycles/day covers oscillations with periods from 4.8 to 12 h. The contours of constant spectral power clearly show the presence of wave activity with different periods and evolution with time. The waves with a period of 4.9 h are seen only during June and December. There are some events with periods of 5.7 and 6.3 h mainly during June solstices. Wave activity is also noted between 6.7 and 7.3 h during both June and December solstices. However, from 7.5 h to 12 h, oscillations with almost all periods are present. The tilts in contours indicate changes in the period of oscillations. The change in the period could be due to the Doppler effects by the mean winds, which may be changing. The 8 h period is present almost all through the year and centred at 8 h. The 8.6 h oscillation, however, shows gaps during equinoxes. The 12 h period is marked by strong power. The straight portion shows the tidal nature of the oscillation. However, there are times when 11.5 h oscillations seem to merge into it. Since the oscillations at some of the periods last for smaller length of time, these may not show significant power in the average spectra.

3.3 Examples of 7.5 h oscillations

One of the advantages of the MF radar is in the continuous data coverage at a number of altitudes. This allows one to study the wave oscillations as a function of height and also to estimate the vertical
The examples of 7.5 h oscillations in the meridional winds during a 20-day period of July 1995 (day 185 to 205) over Davis are shown in Fig. 9. The period of July 1995 is chosen because Forbes et al.\(^\text{13}\) have...
recently reported examples of wave oscillations in the meteor wind data at 95 km near south pole during this period. The duration of the events for this period is slightly longer (about a week). Both the wave events (day number 185-195 and 195-204) show an increase in amplitude with altitude. The amplitude of the first event is ±6 m/s at 84 km and grows to ±9 m/s at 88 km. Also the peak amplitude occurs on day 187 at 92 km, but with a delay at lower altitudes (day 190 at 84 km). The amplitude decreases at higher altitudes. The amplitude of the second event grows from ±4 m/s at 84 km to ±10 m/s at 92 km. The peak activity is seen on day 197 at 92 km and on day 199 at 84 km. Forbes et al. have shown examples of wave oscillations in the meridional wind near 95 km obtained from meteor radar near south pole for the year 1995. The examples shown by them indicate usual wave activity between 7.5 and 12 h, lasting from 2 days to 6 days. However, there are sporadic events with periods between 6 and 7 h. In one of the examples shown by Forbes et al.
for the period 4-19 July 1995, the events with periods between 6 and 8 h and amplitude of ±8 m/s are noted during 6-12 July.

4 Discussion

The mesosphere-lower thermosphere region of the atmosphere (MLT) has gained considerable interest in recent years. Though several important processes take place here, MLT region is least understood. The MLT region is characterized by a number of external forcings. There are enough evidences now that winds/temperature in this region (polar latitudes) show short-term oscillations with periods between 7 and 12 h and identified as Lamb waves. Meyer and Forbes using a global scale wave model (GSWM) showed from numerical simulations that natural responses occur near periods of 14, 9 and 7 h for westward symmetric waves and near 11, 9 and 5 h for westward asymmetric waves for the zonal wave numbers 1, 2 and 3, respectively. Portnyagin et al.10
from recent observations over south pole find most
characteristic period of oscillations uniformly spread
between 7 and 12 h. All the oscillations were
westward-propagating with zonal wave number 1.
Lamb waves and internal gravity wave propagation,
non-linear interaction of the short period tides and
stim excitation of short period waves were suggested
as possible processes for the intra-diurnal oscillations.
The observations of such oscillations reported so far
have been from south pole region only. Our
observations show that these oscillations are global in
nature and occur in the mid-latitude and equatorial
region also. The examples of 7.5 h oscillations at
Davis and Christmas Island during same season also
show nearly similar amplitudes (10 m/s) of the
oscillations.

The wave periods observed in the spectra of the
zonal and meridional winds reported in the present
work at 4, 4.8, 6, 8 and 12 h are related to the solar
tides. The additional peaks at 4.9-5.2, 7.2(7.5),
8.8(9.0) and 10(10.5) h are close to the periods of
gravitational normal modes. Since the wave
oscillations have lifetime of few days only, the mean
spectra do not show prominent peaks as for the tidal
harmonics. The seasonal changes are well marked
with wave activity, spreading to shorter periods
during solstices.

There are other experimental observations of the
waves in the MLT region by MF radar measurements
also. Manson et al.10 and Manson and Meek11
reported periods of 6, 8 and 10 h. Hall et al.12 have
studied the gravity wave features in the upper
mesosphere winds (84-92 km) obtained from three
spaced MF radars located at a triangle with separation
of 500 km in the Canadian region. Hodograph
analysis was applied to study oscillations of 2-10 h
period. Oscillations with periods of around 7-8 h were
noted at all the three sites, indicating the spatial extent
of the oscillations larger than 500 km. From the data
covering the period December 1992-February 1993,
periods ranging between 3.5 and 8 h with a mean
value of 5.5 h were observed. Gravity wave studies
were also made in the mesosphere (70-75 km) using
the MU radar in Japan13. Hodograph analysis of the
data during four campaigns of June 1987, July 1990,
October 1986 and January/February 1991 showed
intrinsic period ranging between 4 and 15 h with a
mean value of 10.2 h. There was no significant
seasonal variation in the observed parameters.

5 Summary and conclusion
Hourly average zonal and meridional winds at five
altitudes between 84 and 92 km at Christmas Island,
Buckland Park and Davis are spectrally analyzed to
study short period oscillations (less than 12 h). Long
series of data and windows of 10, 20 and 40 days give
results with good spectral reliability and resolution.
In addition to the tidal components at 24, 12, 8, 6 and
4.8 h, there are a number of periods between 5 and
11 h. The oscillations with periods between 7.5 and
11 h are common with maximum wave activity during
June solstices and minimum during equinoxes. The
oscillations with periods around 5.0-5.2 h and
7.2-7.5 h are sporadic and occur during solstices only.
The amplitude of 7.5 h oscillations was found up to
±10 m/s at both Davis and Christmas Island. These
oscillations are global in nature.

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