Resonance Lidar studies of gravity wave activity in the low latitude mesosphere region

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Abstract:

In this paper, we present the gravity wave activity in mesospheric sodium (Na), using Resonance Lidar, observed over Gadanki (13.5 °N, 79.2 °E), a low latitude region. In nearly 159 nights of sodium density observations over a period of 2005 and 2006, 21 monochromatic events are obtained. Significant wave activity is seen in the layer over Gadanki and monochromatic waves are evident. The majority of the Na density profiles are associated with downward vertical phase progressions. The observed wave period is in the range of 5 – 30 minutes and the characteristic vertical wavelengths are in the range of about 2 – 6 km.

***Keywords* - Resonance lidar, mesospheric sodium, gravity waves, sodium layer, waves**

I. INTRODUCTION

Gravity waves (GW) are small scale waves excited in the lower atmosphere due to variety of processes, namely, convection, wind shear, land-sea thermal contrast, topography etc, and propagate vertically to the upper atmosphere. GW transport energy and momentum to the mesosphere, where the breaking of these waves causes deceleration of the mean flow [*Fritts and Alexander*, 2003]. There have been a number of observational studies on gravity wave in the middle atmosphere using various techniques [*Fritts and Alexander*, 2003;*Parihar and Taori, 2015*]. Rocket, ground based and theoretical studies of the mesosphere and lower thermosphere show that waves play an important role in the dynamics of the mesosphere and lower thermosphere. It is now believed that the level of gravity wave activity in particular, determines the mean state of the mesosphere. The waves manifest themselves in wind, temperature, density, pressure, ionization and airglow fluctuations in the 80 – 120 km height range and the amplitudes are so large that they can dominate at these altitudes so that the basic state can be extracted only after considerable averaging. Rockets have enabled the density and temperature structure to be measured with excellent height resolution, while long term studies of wind motions using MST, partial reflection and meteor radars and lidar investigations of temperature and density, have enabled the temporal behavior of the waves to be better understood. Important experimental tools for the measurement of individual gravity waves and gravity wave spectra include lidar [*Bills and Gardner*, 1993], radar [*Fritts and VanZandt*, 1993], satellite optical observations [*Mende et al*.,1994] and all-sky imagery from the ground [*Taylor and Hill*, 1991].

However, the information about gravity wave parameters, in particular, over low-latitudes is lacking. It is believed that convective instabilities occurring in the lower atmosphere act as major source for the generation of Gravity Waves [*Fritts*, 1984;] with the convective phenomena being dominant in the tropical region, it is of considerable significance to study Gravity Wave activity over the tropics.

The mesospheric Na layer is an excellent tracer of the atmospheric wave motion. The distortions of meteor trails, variations in mesospheric density and temperature profiles, and the study of upper atmospheric disturbances led to the identification of atmospheric buoyancy waves or internal gravity waves (IGWs) as an important feature of dynamics in the upper mesosphere and lower thermosphere [*Hines*, 1974]. The observed features of meteor trail distortions outlined by *Hines* [1974] are specific to altitudes between 80 and 110 km.

The sodium lidar is a useful tool for studying gravity wave activity and spectra in the mesopause region, especially at high frequencies and high wave numbers, as lidar has high temporal and spatial resolutions of a few minutes and a few hundred meters, respectively. The most extensive lidar measurements of gravity waves have been obtained with systems that utilize resonant backscatter from Na atoms in the upper atmosphere [*Gardner and Voelz*, 1987]. The layer profile is particularly sensitive to gravity wave effects because the wave amplitudes are usually large near the mesopause and the steep Na density gradients on the bottom and topsides of the layer tend to enhance the observed wave perturbations. Sodium lidar studies of gravity waves, although useful, have tended to be more qualitative because of data interpretation difficulties. The response of the layer to waves which propagate through the background atmosphere is not trivial. *Gardner and Voelz* [1985] shows that wave saturation and dissipation effects could also be studied using lidar measurements of Na density profiles. The wavelengths, periods, and amplitudes of these monochromatic waves can be inferred directly from the Na layer profiles or from the spatial power spectra of the profiles [*Gardner and Voelz*, 1987]

Many theoretical studies of gravity waves have also been made, most of which have concentrated on explaining the vertical wave number spectrum, after *Vanzandt* [1982], who first gave the idea of 'universal' atmospheric spectrum similar to the oceanic spectrum. The first widely applied theory on gravity waves was *Dewan and Good's* [1986] linear instability theory. Later, however, several other theories based upon different fundamental physics were also developed, such as the Doppler-spreading theory [*Hines*, 1991], the saturated cascade theory [*Dewan*, 1994], and the diffusive filtering theory [*Gardner*, 1994].

The random wind and density perturbations are best characterized statistically in terms of the gravity wave vertical wavenumber and temporal frequency spectra. The lidar observations over Arecibo (18^o N, 66^o W) reported by *Beatty et al*. [1992] showed increasing gravity wave amplitude with increasing wave period and vertical wavelength. The lidar observations of the gravity wave characteristics over Urbana (40^o N, 88^o W) were found to be similar to those reported for Arecibo [*Gardner et al*., 1989]. *McDonald et al*. [1998] made observations on gravity wave activity using the lidar and MST radar systems at Aberystwyth (52.4^o N, 4.1^o W) and Valentia (51.9^o N, 10.2^o W). They found that the gravity waves vary from night-to-night and have wave periods ranging from 6 to 17 h and vertical wavelengths of the order of 10 km. *Fritts and Alexander* [2003] have reviewed the gravity wave activity in the middle atmosphere and established that the waves with vertical wavelengths greater than 10 km are generally considered to be important in the middle atmosphere dynamics and such long vertical wavelengths (>10 km) are associated with deep convective heating. They also pointed out that the wave amplitudes can grow up to the mesospheric heights with large intrinsic phase speeds and wave breaking or dissipation tends to occur only as waves approach their critical levels. *Gavrilov et al*. [2003] reported maximum gravity wave intensities at the solstices below 83 km, with a shift to the equinoxes at higher altitudes for Hawaii (22^o N, 160^o W), and *Gavrilov and Jacobi* [2004] found the gravity wave perturbations to be maximum at the solstices near 83 km, shifting to equinox near and above 100 km for Collm, Germany (52^{o}N, 15^{o}E). There have not been many studies similar to the above on gravity waves in the middle atmosphere for low latitudes.

The paper is organized in sections as follows. The experiment setup and details about data analysis in extracting gravity wave information from sodium density profiles are described in section 2. Results are described in section 3, Discussions are provided in section 4. Finally, the summary and conclusions of this paper is presented in section 5.

II. EXPERIMENTAL SETUP AND DATA ANALYSIS

An Nd:YAG lidar was set up at Gadanki (13.5 °N, 79.2 °E) under the Indo-Japanese collaboration programme in 1998 (Bhavani Kumar et al., 2007). The lidar system was augmented with capability of probing the mesospheric sodium in January 2005. The system details are described in detail by Bhavani Kumar et al. (2007). Briefly, the broadband Na lidar system at Gadanki was setup in a mono-static configuration with the power-aperture product of 0.35Wm2. The transmitter consists of a tunable pulsed dye laser pumped by a frequency-doubled Nd:YAG laser. The pulsed dye laser is tuned to the D2 resonant absorption line of Na at a wavelength near 589nm. The dye laser employs a dual grating system that is controlled by a computer that enables a rapid selection of transmitted wavelength. The line width of the laser is about 2pm. The dye laser is pumped with 200mJ at 532nm to obtain output pulse energy of 25mJ at 589nm. The dye laser uses Kiton Red as the laser medium. The laser beam is expanded and transmitted into the atmosphere. The receiving system uses a 750-mm Newtonian telescope with field optics and an interference filter. The photomultiplier tube (PMT) is used for photon detection and the output pulses of the PMT are amplified by a broadband amplifier and then fed into a PC-based photon- counting multi-channel scalar (MCS). The MCS counts the pulses in successive time bins. Each time bin is set to 2ms, corresponding to a vertical resolution of 300m. The photon counts are accumulated for 2400 shots, corresponding to a time resolution of 2min. As the laser FWHM spectral width is 2pm (about 1.7GHz), the effective cross-section of the Na atom, which is a function of the laser spectral width, is estimated to be 5.17 $x10^{-16}$ m^2. Then, using this value in the equation for the concentration of sodium, given in Gardner (1989), the sodium concentration profiles are derived (Bhavani Kumar et al., 2007).

The sodium density profiles used in this study are based on mesospheric sodium measurements carried out in all possible cloud free nights (159 nights) during the period January 2005 to December 2006 over Gadanki site. The observation duration per night varies from ~2 to 11 hours. The method of deriving sodium profile from the measured photon count profile is described in Bhavani Kumar et al., 2007. Though we have observations for 159 nights, we scanned all the profiles and we could observe clear nearly monochromatic gravity wave events in sodium density profiles only on 21 nights, based on the following points

1. Sporadic sodium events and meteor induced events are not considered
2. The nights for which data are available for at least 150 minutes are only considered.

The 150 minutes of data are considered uniformly for all the nights centered around large gravity wave activity to obtain the characteristics of the gravity waves.

III. RESULTS

A few examples of the time variation of sodium density are plotted in Figure 1(a,b,c and d) for the days 10 January 2005, 16 February 2005, 30 November 2005 and 24 March 2006. In all the examples presented in figures, which clearly manifest the sinusoidal variations in the vertical profiles that descend with time. These characteristics indicate that the sodium density profiles are perturbed by nearly monochromatic gravity waves with dominant vertical wavelength of a few kilometers. The time evolution of perturbations of sodium layer due to gravity wave activity is also evident. These perturbations are caused primarily by the vertical displacements of the layer by the vertical component of the gravity wave winds. The gravity waves can create spatial modulations of sodium density profiles as well as temporal variations in sodium column density of the short time periods [*Gardner and Shelton*, 1985]. An anomalous feature of these returns is that the peak of the layer remained below 90 km for much of the night (in particular Fig.1 (a) and (b)). Furthermore, the bottomside of the layer undulate throughout the night, passing through a minimum altitude near 0100 hours and having a period of about 1 hour.

The methodology of deriving the gravity wave characteristics is explained by using linear density response theory. However, the characteristics of these gravity waves are derived using the empirical relations adopting the methodology given below. The time and vertical resolutions of sodium density profiles are 120 seconds and 300 m respectively. Hence the Nyquist criteria restrict the gravity waves of periods resolvable to the range 4-150 minutes. As the perturbations in density have been assumed to be due to gravity waves, the mean of sodium density profiles are calculated. It has been shown that a reasonably accurate model for the unperturbed Na layer (background density) is a Gaussian profile [*Gardner and Voelz*, 1987], the mean profile is fitted with Gaussian the fitted curve is removed from each profile to obtain the profiles of sodium density perturbations.

Figure 2 shows three Na density perturbation profiles, averaged for 20 minutes between 01:00 LT and 02:00 LT for 10 January 2005. The width of the Na layer sets the maximum vertical wavelength of the wave interacting with the Na layer. The altitude resolution decides the minimum wavelength detectable. The sinusoidal variation can be clearly observed for all these days. Naked eye observation shows that the perturbations induced by gravity waves having dominant vertical wavelength of around 10 km (for example figure 2). However, this large-scale feature may not be the spectral signature of a gravity wave as suggested by *Gardner and Voelz* [1987] and it reflects the structure of Na layer. Hence we adopted the method recommended by Gardner and Voelz [1987] to obtain the dominant vertical wavelength of gravity waves.

The spatial (vertical) power spectrum of sodium density perturbations is presented in Figure 3(a,b,c and d) for the four days mentioned earlier. The interpretation of the figure is not straightforward, as the peaks in the lower wavelength side may represent the spectral signature of layer, rather than gravity waves. As suggested by *Gardner and Voelz* [1987], the equation for the vertical power spectrum is comprised of three terms. The first one is the signature of the interactive gravity wave, which is proportional to the square of the wave amplitude. This is shown as a local minimum between two peaks [*Gardner and Voelz*, 1987]. The last term represents the second harmonic component of the gravity wave in action (i.e. generated due to non-linear interaction). Briefly, the spectral analysis of *Gardner and Voelz*, [1987] looks for a double humped feature with a minimum at the wavenumber (or wavelength) of the wave.

Following the method of analysis suggested by *Gardner and Voelz,* [1987], the vertical wavelength of gravity waves is estimated by looking for the minimum. In detail, in the lower wavenumber side of the spectral plot (power vs vertical wavenumber), the first peak (which represented the spectral signature of layer and not gravity wave) and valley should be neglected and the valley after the second peak represents the spectral signature of gravity wave (dominant vertical wavelength) and the second minimum after this represent the second harmonic of the dominant vertical wavelength. For example, if the Fig.3(a) is considered, the peak around 10 km vertical wavelength may represent the spectral signature of the peak. Hence leaving this peak, as mentioned earlier, the second minimum corresponding to the wavelength of 3.2 km represents the dominant vertical wavelength of gravity waves i.e. the feature of the principal wave interacting with the Na layer is evident as the local minimum between the first two peaks on the side of the low frequency part of the spectrum, which indicates the characteristic vertical gravity wave number (m_o = 0.31 km^{-1}). This corresponds to approximately 3.2 km wavelength. The other notch between weaker peaks is at about twice the value of the interactive gravity wave number, which corresponds to 0.62 km^{-1}, which corresponds to approximately 1.6 km, generated due to non-linear process. The vertical wavelengths of order 3 km have been observed by using lidars, radars and rockets at the mesopause region [*Williams et al*., 2006a]. Usually long period waves such as tides are associated with shorter wavelengths [*Williams et al*., 2006a]. The phase velocity of the wave is estimated by dividing the vertical distance the individual wave fronts travel by time between successive observations. The vertical velocity of the wave can be estimated by looking at the motion of the successive peaks, as shown by the Figure 1(a). The apparent phase velocity is about 1.0 km h^{-1} or 30 cm s^{-1}, which is consistent with the reported values of the semidiurnal tide in Na layer [*Kwon et al*., 1987]. The dominant vertical wavelength of the gravity waves can be inferred through naked eye itself in the sodium density profiles presented in Figure 1(a) by noting three peaks in the altitude region 87 to 97 km. This feature is particularly prominent around 01:30 IST.

The mean power spectrum for 16 February 2005 is shown in Figure 3(b) shows the characteristic vertical gravity wave number (m_o=0.47 km^{-1}). This corresponds to approximately 2.1 km wavelength. The other notch between weaker peaks is at about twice the value of the interactive gravity wave number, which corresponds to 1 km^{-1}, and corresponds to approximately 1 km wavelength, generated due to non-linear process.

Figure 3 (c) shows the mean power spectrum on 30 November 2005. In this spectrum we observed the characteristic vertical wavelength of 5.6 km. The other peak is coming around 3.2 km. Figure 3(d) shows the mean power spectrum on 24 March 2006 between 0440 and 0540 LT. The vertical gravity wave number on 24 March 2006 is 4.8 km and secondary peak is coming at 2.5 km.

Using this method, the dominant vertical wavelengths for all the 21 events are estimated. It can be inferred that the dominant vertical wavelengths are below 5 km in most of the events (19 events). In particular, the vertical wavelength is in the range 3-4 km in 11 events.

In order to find the dominant period of the gravity waves, the perturbation profiles are subjected to Fourier transform in of time domain and it is averaged for four altitude ranges (83-85 km, 87-89 km, 91-93 km and 95-97 km). The minimum period that can be observed is a function of the temporal resolution of the data. In Gadanki observations, the 2-min.integration time limits the observations to periods of about 4 min. or longer. The frequency spectra are displayed in figure 4(a) on 10 January 2005 from 84 to 96 km with an interval of 4 km. The frequency spectra for entire data interval averaged over altitude of 84 to 96 km on 10 January 2005 reveal that the domainant wave period of the waves around 29 minutes.

Figure 4(b) shows the frequency spectra for different height levels between 84 and 96 km on 16 February 2005. The mean wave period on 16 February 2005 is approximately 15 minutes. Frequency spectra on 30 November 2005 are shown in figure 4(c). The mean wave period on 30 November 2005 is 21 minutes. Figure 4 (d) shows the frequency spectra on 24 March 2006. In this spectrum the mean observed period is around 11 minutes. Using this analysis, the dominant periods for all the 21 events are analyzed. From this, the dominant period of the wave is around 10-20 minutes in most of the events (15 events). In two events, the wave period is in the range of 5-10 minutes and in four events, it is in the range of 20-25 minutes. There is no preferential wave period to any particular season.

IV DISCUSSIONS

Gardner and Voelz [1987] analyzed 109 wave events observed at Urbana over a 3-year period (1984 – 1986), while *Beatty et al*. [1992] presented observations of 62 events made between January and April 1989 at Arecibo. In contrast with that, we have observed only 21 events over Gadanki during 2005 and 2006 because sporadic sodium events and meteor induced events are not considered and the nights for which data are available for at least 150 minutes are only considered. *Richter et al*. (1981) showed wavelike structures in the sodium layer have been observed with typical wavelengths of 3 – 15 km. In the mesosphere, Na layer studies at Urbana also showed vertical wavelengths in the 2- 15 km range [*Gardner and Voelz*, 1987]. *Beatty et al*. [1992] showed that the most common vertical wavelengths were between 4 and 8 km. *Yong et al*. [1998] observed that the vertical wavelengths range between 1 and 10 km at Wuhan (30 ^{o} N). These values are comparable with the present observations whose vertical wavelengths are in the range of 2 - ~7 km.

Gardner and Voelz [1987] observed that the periods vary between 25 and 800 min at Urbana. The most common observed wave periods in the mesopause region were in the range of 10 - 100 minutes [*Beatty et al*., 1992]. The Gadanki observed wave periods also vary between 5 to 25 min. The waves with a wider range of periods and vertical wavelengths were measured at Urbana and Arecibo than at the south pole and Syowa. High-frequency, short-wavelength waves (observation periods were less than 1 hour and vertical wavelength were less than 2-3 km) constitute approximately half of the gravity waves observed at Arecibo [*Beatty et al*., 1992]. As the energy of gravity waves is much larger than that for shorter wavelength gravity waves, and the density perturbation is mainly induced by the gravity waves with longer wavelengths, then as the maxima in the total perturbation and the variance for fluctuations with vertical scales between 2 and 10 km occur near the equinoxes.

V. SUMMARY AND CONCLUSIONS:

Sodium lidar is a useful technique for studying the characteristics of monochromatic gravity waves in the upper mesosphere. The layer profile is particularly sensitive to gravity wave effects because the wave amplitudes are typically large near the mesopause and the steep Na density gradients on the bottom and topsides of the layer tend to enhance the observed wave perturbations. The gravity wave lidar measurements of mesospheric Na density at 80 – 110 km observed by means of the broadband sodium resonance lidar obtained on 159 nights spread over throughout the years 2005 and 2006 at Gadanki. In nearly 159 nights of sodium density observations, 21 monochromatic events are obtained. Significant wave activity is seen in the layer over Gadanki and monochromatic waves are evident. These result shows that the majority of the Na density profiles are associated with downward vertical phase progressions which are characteristic of upward propagating gravity waves. At Gadanki, the observed wave period is in the range of 5 – 30 minutes and the characteristic vertical wavelengths are in the range of about 2 – 6 km.

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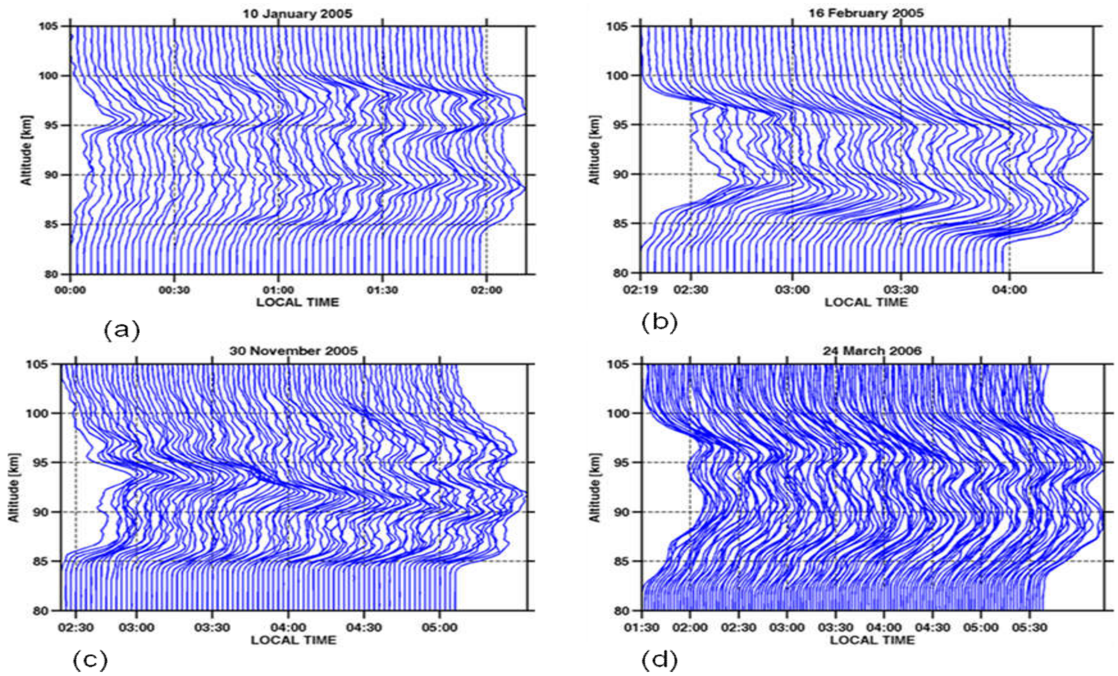

Fig. 1 A time sequence of vertical profiles of Sodium density observed on the nights (a) 10 January 2005 (b) 16 February 2005 (c) 30 November 2005 (d) 24 March 2006.

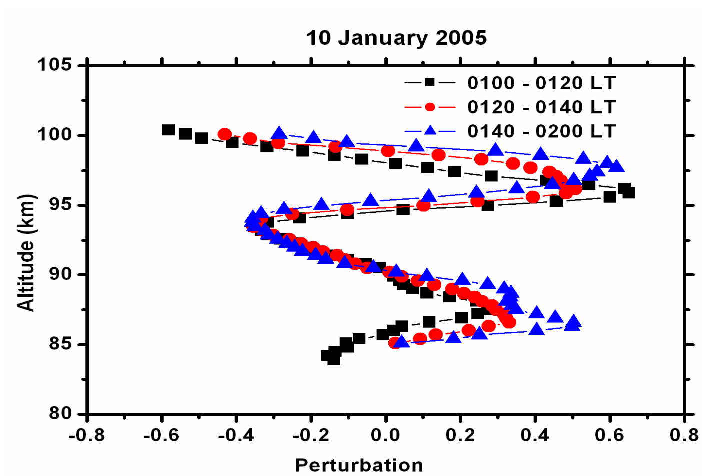

Fig. 2 Perturbation profiles derived from Na profiles for 10 January 2005 averaged for 20 min during the time interval between 0100 & 0200 LT.

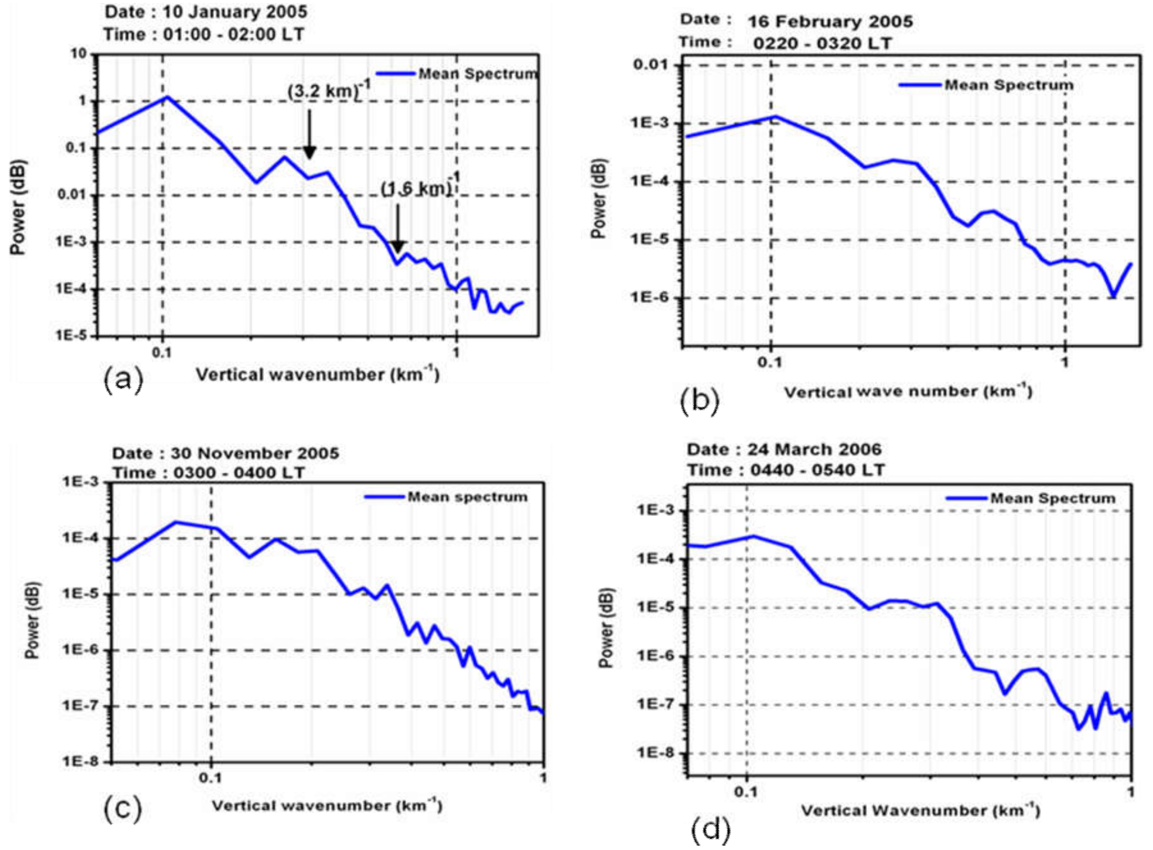

Fig. 3 Vertical wavenumber spectra for the sodium density fluctuations on (a) 10 January 2005 (b) 16 February 2005 (c) 30 November 2005 (d) 24 March 2006.

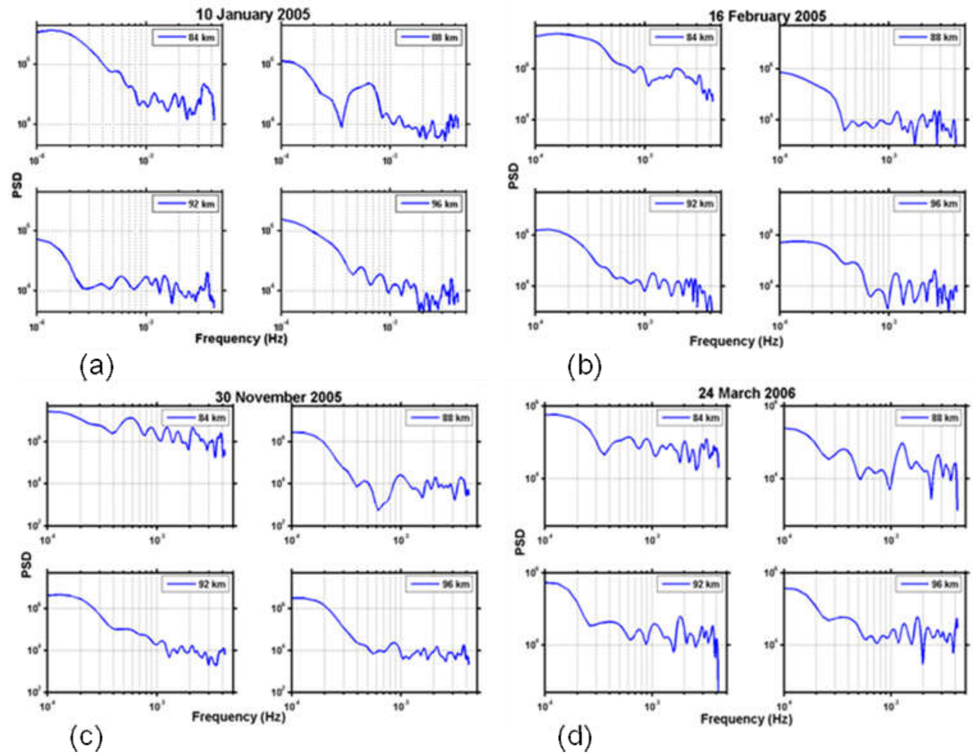

Fig 4 Power spectral density (PSD) versus frequency of the sodium fluctuations for the nights (a) 10 January 2005 (b) 16 February 2005 (c) 30 November 2005 (d) 24 March 2006.