Time-spatial parameters of internal gravity waves in the mesosphere-lower thermosphere region derived from meteor radar wind measurements

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Zusammenfassung

Eine verbesserte Methode zur Erfassung der Parameter interner Schwerewellen mit Hilfe von Winddaten eines Meteorradars wird vorgestellt. Die Analyse basiert auf der Einteilung des Messvolumens in Untervolumina und der Waveletanalyse der Windmessungen in diesen, mit anschließender Bestimmung der Phasenlage der spektralen Maxima. Auf diese Weise ist zum ersten Mal eine Statistik von Schwerewellenparametern aus Meteorradardaten unter Einschluss der horizontalen und vertikalen Wellenlängen und Ausbreitungsrichtungen erstellt worden. Es zeigte sich, dass sich der größte Teil der Schwerewellen sich oben ausbreitet. Hochfrequente Wellen mit Periodendauern unter 2 Stunden dominieren. Die Verteilung der erfassten Wellen innerhalb eines Tages zeigt eine geringe Struktur, mit Maxima am Morgen und Abend.

Summary

In this paper a modified procedure of revealing the parameters of internal gravity waves from meteor radar wind data is described. The method bases on dividing the measuring volume into different volumes, and, using wavelet analysis, calculating phase progression of frequency peaks in height and in the horizontal. Thus, for the first time the distribution of vertical and horizontal wavelengths and directions of IGW energy propagation using meteor radar data has been obtained. The majority of waves have been found to propagate upwards. High-frequency waves are dominating. The distribution of waves in the course of the day is only weakly structured, with weak maxima in the morning and evening.

1 Introduction

Studies of the wind regime in the mesosphere/lower thermosphere (MLT) regions have shown the essential influence of internal gravity waves (IGW) on dynamic processes and energy transport and dissipation in these height layers (e.g. Gavrilov, 1974; McLandress, 1998). Propagating from below, but partially also originating in the middle and upper atmosphere, they can produce turbulence and substantially deposit momentum and energy, and they can influence the general circulation, thermal regime, and composition of the middle and upper atmosphere (Gavrilov et al., 2000, 2002).

During the last decades, radar measurements have successfully been used to provide information about IGW. These measurements have been carried out using the Japanese middle and upper atmosphere (MU) radar at Shigaraki (Yamamoto et al., 1987; Gavrilov et al., 1996, 1997, 2002), medium frequency (MF) radar (Gavrilov et al., 1995; Manson et al., 1999, 2003), and even the low frequency (LF) ionospheric E-region drift measuring method (Gavrilov and Jacobi, 2004). In addition, meteor radar measurements have been used to derive IGW information (Kalchenko et al., 1985; Williams et al., 1999; Oleynikov and Kashcheyev, 2002; Xiong et al., 2003; Manson et al., 2004). However, thus far detailed parameters of IGW, as horizontal wavelength and energy propagation direction has not been available from meteor radars, but only from more sophisticated Mesosphere-Stratosphere-Troposphere (MST) radars with controllable beam direction.

In this paper results of a meteor radar study carried out using an automatic goniometer of a meteor radar station at the Kharkiv National University of Radioengineering (49°30' N, 36°51' E) are presented with the purpose to obtain the individual time-spatial parameters of IGW and to determine features of their statistical distribution. The automatic goniometer of the Kharkiv meteor radar station (AG MRS) is intended to study dynamic parameters of the Earth atmosphere at altitudes 80-105 km with the opportunity of revealing the high-altitude structure of wind motions. AG MRS, operating on 36.9 MHz, consists of a five-element antenna array that is directed to the East, and makes Doppler measurements of the radial drift velocity, angular data (azimuth and elevation), and slant distance up to the reflecting area of meteoric trails (Oleynikov, and Kashcheyev, 2002).

2 Technique of data processing

The algorithm to process the meteor radar data to obtain information about IGW parameters bases on that described by Gavrilov (1981) and Kalov and Gavrilov (1985). The zone that is surveyed by the meteor radar is divided into several regions of 6 km height and 60 km (in some cases 80 km) width, to ensure a sufficient number of meteors in each subvolume These subvolumes are constructed for the entire height layer under consideration (80-100 km), with a height shift of 2 km, i.e. with 4 km overlap. Similarly, in the horizontal the zone between 80 and 220 km distance is considered, with a horizontal step of 10 km or 20 km. We use horizontal wind velocities, which have been band-pass filtered before further processing. From the spectra calculated by Fourier transform for each separate region, mean spectra for each altitude range has been obtained. Simultaneously, the spectrum is divided into a coherent component of spectral density, and a noise component. The presence of a maximum in the spectrum is a necessary condition for detecting an IGW with the respective frequency. The identification of the IGW is then carried out as follows, and after the following criteria:

- the maximum in the average spectrum must be visible in several consecutive altitude layers, and the maximum must be found in the spectra of different ranges at one height,
- a close to linear phase change of the wave with distance and altitude is necessary,
- a S/N ratio > 1,
- the width of the maxima in the spectrum does not exceed the frequency filter width.

The cases selected by these criteria then are analysed to determine time-spatial and energetic IGW parameters. Some lacks have been revealed during the study of this algorithm:

- the algorithm does not take into account deterioration of IGW during the time window for the Fourier transform,
- the Fourier transform may add harmonics to the spectrum, which complicates revealing the nearby waves.
- The least square fitting, which is used for estimating range–phase and an altitude–phase dependencies, is very sensitive to possible outliers in the processed data.

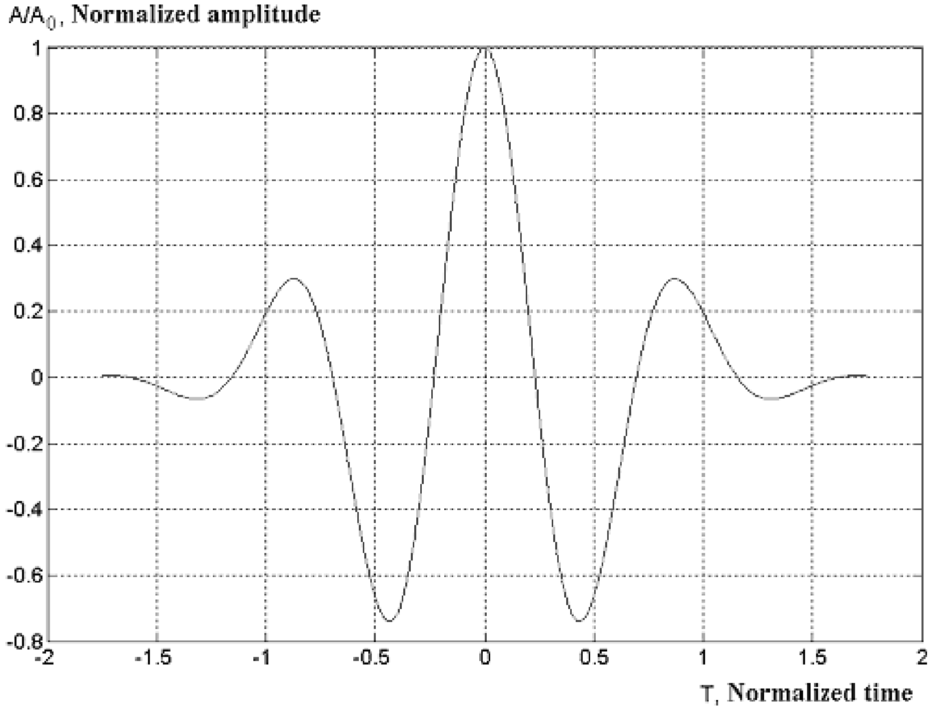
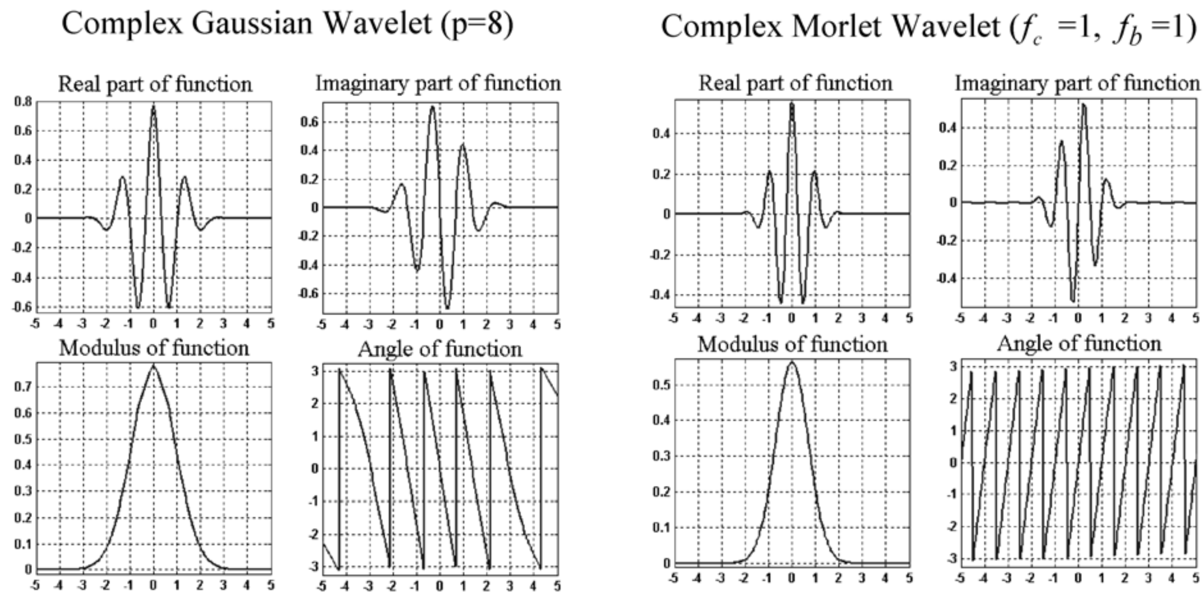


Figure 1: Characteristic amplitude development for IGW.



$$\psi_p(x) = C_p \left(e^{-jx} e^{-\frac{x}{2}} \right)^{(p)}$$

– p – wavelet order

– C_p – constant

(a)

$$\psi(x) = \sqrt{\pi f_b} \cdot e^{j2\pi f_c x} e^{-\frac{x^2}{f_b}}$$

– f_c – wavelet center frequency

– f_b – bandwidth parameter

(b)

Figure 2: Characteristics of the complex Gaussian (a) and Morlet (b) wavelet.

A review of the available dataset showed that IGW amplitude variations can be described using a temporal development of the amplitudes as shown in Figure 1. Therefore, to eliminate the abovementioned lacks in the IWG detecting algorithm, a modified process is used, including wavelet analysis to obtain amplitude and phase spectrum. This way of spectrum analysis is preferable for two reasons. Firstly, the wavelet analysis can be carried out with mother wavelet functions that are similar to original IGW structure (see Figure 2). Secondly, there is no necessity to choose the time window for spectrum analysis, because the wavelet analysis "is adapted" to finding signals with various duration. Two mother wavelet functions applied here for detecting IGWs and their analytical expressions are shown in Figure 2.

The next step in processing the data is a robust least square fitting for detecting phase dependences. It is usually assumed that errors can be described by a normal distribution, and that extreme values are rare. However, extreme values, so-called outliers, do occur. The main disadvantage of simple least squares fitting is its sensitivity to those outliers, because squaring the residuals magnifies the effects of these extreme data points. To minimize the influence of outliers, it is therefore offered to use a robust least squares regression method. Robust fitting allows reducing miscalculation of horizontal and vertical length of the gravity wave with outlier in a dataset (Holland and Welsch, 1977; Huber, 1981; Street et al., 1988; DuMouchel and O'Brien, 1989).

Taking into account the arguments stated above, the following algorithm of detecting IGW parameters using the meteor radar wind data is used. First, the measuring volume is divided into several height layers and range zones, with mean values h_i and d_i. Then a sliding window low-pass filter is applied to suppress random errors in the high frequency component of the meteor radar wind time series. The size of the sliding time window is 10 minutes, so that frequency component with periods less than 5 minutes will be suppressed. From the time series 5-minute averages are calculated; this allows detecting IGW with periods of more than about 30 minutes. A continuous wavelet transform with complex 8-order Gaussian or complex Morlet wavelet with parameters $f_c = 1$ and $f_b = 1$ was carried out. These complex mother wavelets have been found to be the most suitable for IGW modelling. Using the horizontal wind velocity wavelet spectra for separate range zones d_i, an average wavelet spectrum is computed for each altitude layer h_i, and times and frequencies of wavelet spectrum maxima are determined.

The range–phase dependence of the IGW is constructed from the spectra in each range and height zone using robust least square fitting, with check of a hypothesis about a linear regression for the range–phase dependence data (Brandt, 1975), and the horizontal wavelength and phase speed of the IGW is calculated. The altitude area, in which the calculated horizontal wavelengths do not deviate more than the rms deviation from their mean value, is accepted to be the spatial area where the wave is present. A vertical IGW structure check is applied. For each altitude layer h_i the mean values of phase and altitude are calculated, from that the vertical phase dependence is constructed, again using robust least square fitting and the hypothesis about linear regression. Finally, the dispersion relation is checked, i.e. it is tested whether the IGW phase velocity satisfies the expression (Gavrilov and Medvedev, 1997):

$$c \leq c_{max} = 2NH \ ,$$

with c as horizontal phase speed, N as Brunt–Väisälä frequency, and H as the scale height.

3 Results

The above-described algorithm was applied to the meteor radar wind data that was obtained during 2 summer campaigns in July–August 1998 and 1999. Background winds and long-period waves during these campaigns have been presented in Jacobi et al. (2001) and Pancheva et al. (2002a,b, 2003). Using data of these 124 days, more than 1500 waves and their time-spatial parameters are determined.

Histograms of vertical and horizontal IGW wavelength are shown in Figure 3. For convenience, positive wavelength values correspond to upward and westward propagation of IGW energy, while negative values – to downward and eastward propagation of IGW energy. The most probable values of the vertical wavelength λ_z are 10-30 km, for any direction of IGW propagation. Upward propagating waves are more frequent (65% of all waves) than downward propagating (35%), which is in accordance with the theory of IGWs (Hines, 1975, Andrews et al., 1987). The dominant horizontal wavelengths lie between λ_x=100-500 km. There is no pronounced difference between the frequency of occurrence of eastward and westward propagating waves (56 % vs. 44 %).

(a) (b)

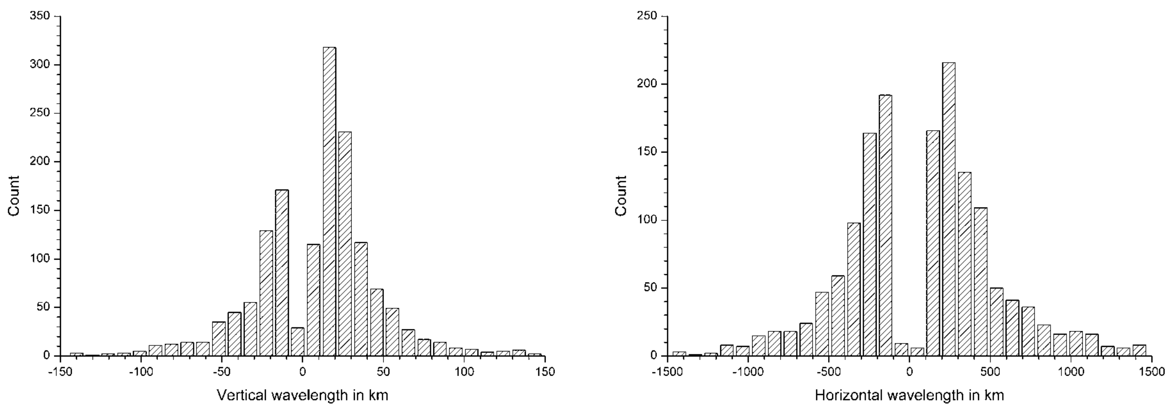


Figure 3: Histograms of vertical (a) and horizontal (b) IGW wavelength.

(a) (b)

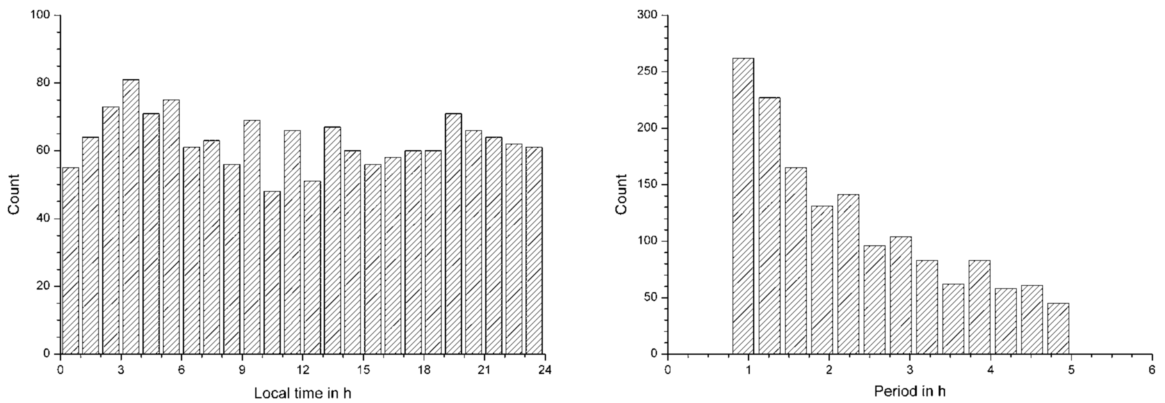


Figure 4: Histograms of IGW occurrence during the day (a) and period distribution (b) of IGWs. The upper and lower limits in panel (b) are due to the resolution limitations of measurements and data analysis procedure.

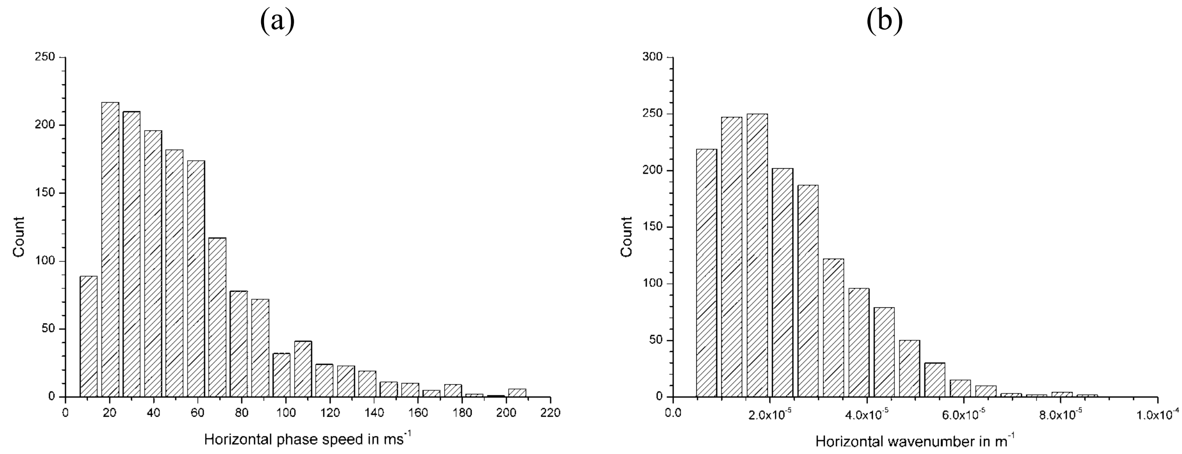


Figure 5: Histograms of horizontal phase velocity (a) and horizontal wave number (b).

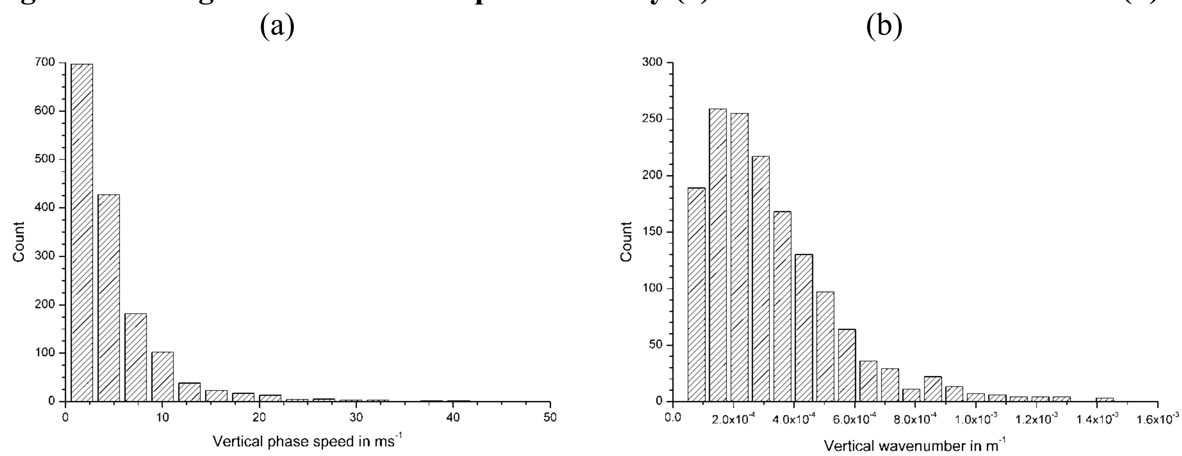


Figure 6: Histograms of vertical phase velocity (a) and vertical wave number (b).

In Fig. 4, histograms of IGW periods and the time of day of their occurrence are shown. The histogram of the IGW daily cycle (Fig. 4a) has two weak maxima at early morning and early evening. The histogram of IGW periods (Fig. 4b) displays an exponential dependence. Prevailing are high-frequency IGW with the periods 0,8-2 hours are prevailing. The probability of occurrence IGW decreases with increasing period.

Histograms of horizontal phase velocity and horizontal wave number are shown in Fig. 5, while histograms of vertical phase velocity and vertical wave number are shown in Fig. 6. From the wavenumber distribution it can be seen that the maximum of occurrence is found near 400 km for the horizontal wavelength (horizontal wavenumber of about $1.5 \cdot 10^{-5} m^{-1}$), and 30 km for the vertical wavelength (vertical wavenumber of about $0.2 \cdot 10^{-3} m^{-1}$).

In Figure 8 and Figure 8 the dependences of horizontal and vertical phase velocities and wavenumbers on IGW frequency are shown. IGW phase velocities increase with frequency, which is true for both the horizontal and the vertical component. The correlation is significant at the 99% level. A similar situation is observed for the wavenumber dependence on frequency, however, the correlation between vertical wavenumber and frequency is very weak.

The obtained distributions of time-spatial IGW parameters agree well with the results of other authors. In earlier works (Gavrilov et al., 1996, 1997; Kalov and Gavrilov, 1985; Gavrilov and Medvedev, 1997) results about a horizontal IGW structure are received. Their distribution of horizontal IGW phase velocity, distribution of horizontal wave number, and also their dependence on IGW frequency, have similar character and are quantitatively of the same order of magnitude, as has been shown here. However, Kalchenko et al. (1985) and

(a) (b)

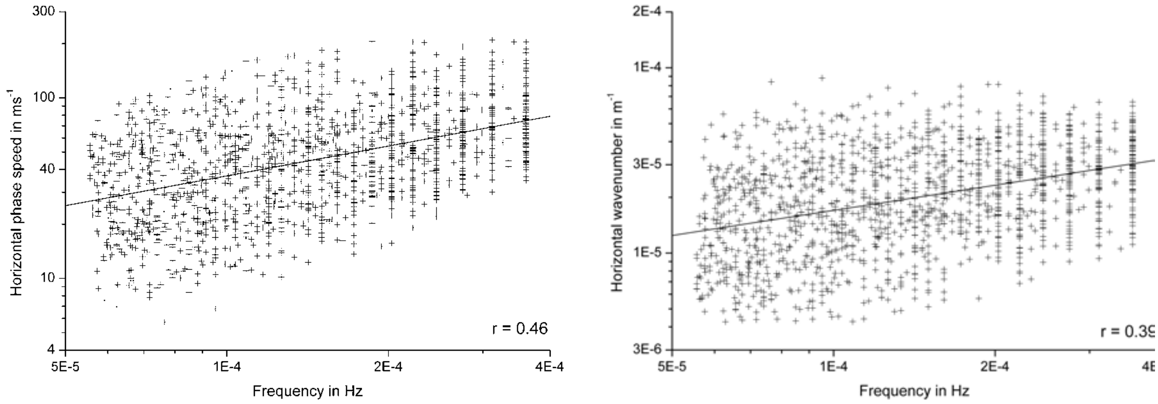


Figure 8: Dependence of the horizontal phase velocity (a) and wavenumber (b) on IGW frequency. Upper and lower frequency limits are due to limitations in data analysis and measurements.

(a) (b)

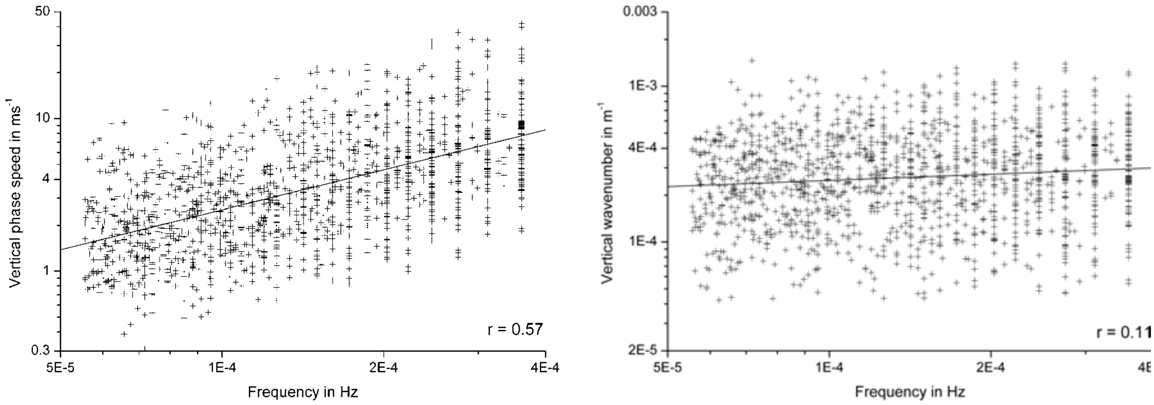


Figure 8: As in Figure 8, but for the vertical wave characteristics.

Gavrilov et al. (1996, 1997) showed a more uniform IGW frequency distribution, while the received distribution of IGW periods shown in Figure 4, shows a clear domination of high-frequency IGW, i.e. of short-period waves.

4 Conclusion

In this paper a procedure of revealing the parameters of internal gravity waves from meteor radar wind data using wavelet analysis is described. The use of the described algorithm has allowed us to identify waves and determine time-spatial IGW parameters. For the first time the distribution of horizontal and vertical wavelengths and directions of IGW energy propagation using meteor radar data has been obtained. Considering the fact that meteor radars with interferometric meteor position finding are frequently and increasingly used in upper mesosphere/lower thermosphere studies this gives the potential of analysing IGWs and their impact on the background circulation on a global scale.

The majority of waves have been found to propagate upwards, although the portion of downward propagating waves is non-negligible. High-frequency waves are dominating. The distribution of waves in the course of the day is only weakly structured, with weak maxima in the morning and evening.

The dataset used is limited to the 2-month campaign in summer 1998. Therefore in this study no information on the seasonal cycle of gravity wave activity and the potential variation of IGW parameters with season could be obtained. Further studies will be performed using a larger set of AG MRS data.

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