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A statistical study of internal gravity wave characteristics using the combined Irkutsk Incoherent Scatter Radar and Digisonde data

A.V. Medvedev*, K.G. Ratovsky, M.V. Tolstikov, S.S. Alsatkin, A.A. Shcherbakov

Institute of Solar–Terrestrial Physics, Siberian Branch, Russian Academy of Sciences (ISZF SO RAN), P.O. Box 4026, Irkutsk 664033, Russia

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ABSTRACT

Using previously developed methods for determining the three-dimensional spatial–temporal structure of traveling ionospheric disturbances and the automatic detection of wave disturbances, we analyzed data obtained simultaneously with the Irkutsk Incoherent Scatter Radar and Irkutsk ionosonde. The analysis relies on long continuous series of observations acquired during winter seasons in 2010–2014. We obtained representative statistics of traveling ionospheric disturbances characteristics including the full velocity vector. We analyzed the characteristics of traveling ionospheric disturbances with 1–6 h periods comparing them against the dispersion relations for internal gravity waves in the Boussinesq and Hines approximations. It was shown that, with due consideration for the horizontal neutral wind, most of the observed ionospheric disturbances agrees with the laws of internal gravity waves propagation in the upper atmosphere. It was found that azimuthal anisotropy of internal gravity waves characteristics allows us to obtain the diurnal variations of zonal and meridional neutral winds in the upper atmosphere.

1. Introduction

The ionosphere usually exhibits fluctuations in plasma parameters of different time and space scales that can travel considerable distances without significant change of their shape. These fluctuations are commonly referred to traveling ionospheric disturbances (TID). For more than half a century, observations of TIDs have provided a huge body of empirical data (Beynon, 1948; Munro, 1949). However, there are still a lot of questions we cannot answer without new research methods allowing us to measure the full vector velocity of TID, for example, the question concerning sources of TIDs. The main source of TIDs is considered to be internal gravity waves (IGW) (Hines, 1960). For IGW, the wave elevation angle depends on the wave frequency. The simplest approximate version of this relation is the Boussinesq dispersion equation when the ratio of the wave frequency to the Brunt–Vaisala frequency (medium parameter) determines the elevation angle. A more complicated version, Hines dispersion equation (Hines, 1960), also accounts for the wavelength and acoustic cut-off frequency. There are more accurate and complex dispersion relations taking into account many other medium parameters (Vadas and Fritts, 2005; Rudenko, 2013), but in the first approximation the IGW frequency and the Brunt–Vaisala frequency determine the elevation angle. The assumption that the most of TIDs are ionospheric manifestations of IGW may be confirmed by verification of the dispersion relations. These efforts may provide an experimental support for theoretical ideas about the peculiarities of IGW propagation in the thermosphere. These questions are topical in modern geophysics because IGW significantly contribute to the general atmospheric circulation, provide a connection between lower, middle, and upper atmosphere, and have an effect on climate (Alexander et al., 2010). Determining the TID elevation angle can be quite a challenge because this requires measurements of disturbance vertical profiles at ionospheric heights at least at three spaced points simultaneously. This objective can be best achieved through the use of incoherent scatter radars with rapid electronic beam-steering capability or complexes of radio physical equipment with different principles of operation (Ratovsky et al., 2008; van de Kamp et al., 2014). One of the first verifications of the dispersion relation for IGW was made by Williams et al. (1982). The study showed a reasonable agreement between the Hines equation and the ~40-min TID characteristics and the task of the neutral wind consideration was also problematized. In the linear approximation, the interaction between IGW and the horizontal wind leads to the Doppler frequency shift: the larger the wind velocity and the TID period, the larger the shift is Ma et al. (1998) obtained the height variations in the elevation angle from $\sim -80°$ to $\sim -40°$ for the ~70-min TID. Without considering a neutral wind effect, this corresponds to variations in the Brunt–Vaisala period from ~12 min to ~1 h.

* Corresponding author.
E-mail address: medvedev@iszf.irk.ru (A.V. Medvedev).

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Considerable variations in the Brunt–Vaisala period with height and ~1-h Brunt–Vaisala period do not seem to be physically realistic. Our measurements (Medvedev et al., 2009, 2013) for more than 1-h TIDs also yielded unrealistic values of the Brunt–Vaisala period without considering the wind. Direct measurements of the full wind-velocity vector at ionospheric heights are rare; incoherent scatter radars can determine only its meridional component, and model values are adequate only to describe the average background wind. Using the model medium parameters (e.g. the Brunt–Vaisala period), we can obtain the wind along the TID propagation direction under the assumption that the dispersion relation is valid, as it has been done by Vadas and Nicolls (2008). However, the wind velocity estimations using this approach from single measurements may considerably (up to sign reversal) differ from model velocities, and we can not verify the estimations. Only with available representative statistics on TIDs propagation parameters, can we get steady-state data on wind velocity, which will allow comparison with models. The Institute of Solar-Terrestrial Physics has developed a unique complex of radio physical instruments for ionospheric research and a method for studying three-dimensional spatial–temporal structure of wave disturbances (Potekhin et al., 2008; Ratovsky et al., 2008; Medvedev et al., 2009). This method relies on data acquired by the DPS-4 ionosonde and the Irkutsk Incoherent Scatter Radar (IISR) that is able to scan in the meridional plane. In this study, using a representative statistics on measurements of the full vector of TIDs velocity, we analyze the TID characteristics comparing them against the dispersion relations for IGW in the Boussinesq and Hines approximations. Diurnal variations of zonal and meridional neutral wind velocities in the upper atmosphere are obtained based on the azimuth anisotropy of IGW characteristics.

2. Observational results for TID characteristics

Initial data are electron density profiles measured with two oblique beams of IISR and a vertical beam of the DPS-4 ionosonde. The DPS-4 ionosonde is located in Irkutsk. The Incoherent Scatter Radar (Potekhin et al., 2008) is 98 km northwestward of Irkutsk. In the mode of TID characteristics measurements, the radar performs scanning with a time step of 40 ms, alternatively in two directions, which allows almost simultaneous measurements of scattered signals height profiles by means of two oblique beams with integration time from 1 to 10 min. The ionosonde measures electron density profiles with a time step of 15 min. Thus, the instruments give three electron density profiles estimated independently of each other at spaced points. All electron density profiles are interpolated to 15-min step on time. The relative positions of the instruments form a basis with a typical scale of ~100 km and provide measurements of the TID dynamic characteristics. Using lags between electron density disturbances, observed with two IISR beams and the ionosonde, at each height we obtain a system of linear equations for the full velocity vector of TID. Methods of determining TID propagation parameters are described in detail by Medvedev et al. (2009) and Ratovsky et al. (2008). Processing long series of measurements requires automated ways of identifying ionospheric disturbances. Vlasov et al. (2011) processed the incoherent scatter radar data for the TID analysis as follows. The dominant frequency components in ionospheric fluctuations were carefully selected automatically by the software; and the band-pass filtered data for these dominant frequencies were produced. Then, the filtered data were manually examined to exclude auroral phenomena.

In our method any manual data processing is completely excluded. The automatic software-based method for identifying TIDs assumes that the energy of the TID spectrum is mainly concentrated in the dominant harmonic. The existence of local spectral maximum at the same frequency at three neighboring heights (at least) for each of the tools (the ionosonde and two IISR beams) is the criterion of the presence of a wave disturbance. The method is described in detail by Medvedev et al. (2013). The developed method allows us to study disturbances that have both downward- and upward-propagating phase fronts.

The developed method has been used to process long series of electron density profiles (from 16 January to 16 February 2011, from 17 January to 9 February 2012, from 25 December 2012 to 21 January 2013, from 26 December 2013 to 12 January 2014) with determination of the full velocity vector for 1–6 h ionospheric disturbances corresponding to IGW. Distribution of observed events is presented in Table 1.

Table 1
Distribution of observed events.

Observation period	Hours suitable to processing by automated method	Average number of TIDs per day
2011 Jan. 16–2011 Feb. 16	505	79
2012 Jan. 17–2012 Feb. 9	255.5	61
2012 Dec. 25–2013 Jan. 21	415.75	115
2013 Dec. 26–2014 Jan. 12	195.25	135

Fig. 1 presents the distribution of the TIDs observation time.

Here and after, the relative frequency is the ratio of the number of disturbances with a fixed parameter to the total number of disturbances. Fig. 2 illustrates the azimuth distributions. The azimuth is measured clockwise from north. As it is seen from Fig. 2, the predominant directions of TIDs are from north to south and from south to north. Fig. 3 depicts the elevation angle distributions.

The elevation angle is measured from the horizon; the positive elevation angle corresponds to the upward phase velocity; the negative one to the downward phase velocity. Most of TIDs have a downward phase velocity (negative elevation angle), which corresponds to IGW propagating from the source located under the region considered. Later in this paper, we will interpret positive elevation angles comprising 20% of all the observations. Fig. 4 shows the TID magnitude velocity distributions.

Fig. 4 suggests that the peak in the distributions is between ~25 and 50 m/s. Fig. 5 presents the TID wavelength distributions.

The peak in distributions of wavelengths is between 100 and 200 km, which agrees with theoretical estimates (Vadas, 2007).

3. Verification of dispersion relations

The obtained statistics allows us to verify the agreement between the TID propagation characteristics and theoretical concepts of the IGW propagation in the upper atmosphere. We tested all the wave disturbances for the correspondence to the dispersion relations of Boussinesq (Pedlosky, 2003)

$$\omega^2 = \Omega_B{}^2(k_x^2 + k_y^2)/k^2 = \Omega_B{}^2 k_h^2/k^2 = \Omega_B{}^2 \cos^2\theta \tag{1}$$

and Hines (1960).

$$k^2 = \frac{k_h^2 \Omega_B{}^2}{\omega^2} + \frac{\omega^2 - \omega_A^2}{C_0^2} \tag{2}$$

where ω is the TID frequency, k is the wave vector, Ω_B is the Brunt–Vaisala frequency, θ is the elevation angle, k_h is the horizontal wave number, C_0 is the sound velocity, and ω_A *is* the acoustic cut-off frequency.