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Structure of Planetary Disturbances of the Mid-Latitude Ionosphere According to Observations of GPS Satellites

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Abstract—Using GPS satellites, the existence of ionospheric disturbances in the range of planetary wave periods is established based on global variations of the total electron content in the mid-latitude ionosphere in the summer months of 1990. For quasi-two-day variations, a substantial difference is found of the structure of these variations from variations with the same quasi-period in the atmosphere. In addition, it is demonstrated that the ionospheric response to quasi-seven-day atmospheric variations is a more general phenomenon than was commonly believed before. The observed variations of the total electron content are interpreted as a consequence of the modulation of tidal oscillations by planetary waves.

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INTRODUCTION

Apparently, as the first observations of ionospheric variations with periods typical for atmospheric planetary waves (2, 5, 10, and 16 days) one can consider the discovery of 5-days variations of ionospheric absorption of radio waves (*D*-region) which were associated with simultaneous 5-days waves in the stratosphere [1]. Later, in ground-based observations quasi-16-days oscillations of the magnetic field horizontal component were detected and simultaneous oscillations of the critical frequency of the *F*-layer of the ionosphere [2]. It was suggested to consider these oscillations as a consequence of penetration of energy of planetary waves to the ionosphere altitudes. According to data of the global network of ionosondes (over a period of 20 years) quasi 2-days variations of the critical frequency of the *F*-layer were found to be sometimes in a good correlation with quasi-two-days waves in the mesosphere [3]. One cannot but be surprised by all these results, since simulations of propagation of the planetary waves into the upper atmosphere show [4] that these disturbances do not penetrate higher than 100 km.

In recent studies [5–10], in line with the results generally confirming the similarity of disturbances in the atmosphere and in different ionospheric layers, some mechanisms of links between the thermosphere and ionosphere were suggested, but also the attention was attracted to obvious discrepancies between expected and observed disturbance patterns. In particular, disturbances in the mesosphere and *F*-layer of the ionosphere mainly correlate, but at the same time one can find no correlation between the stratosphere and mesosphere; there can also be no correlation between the mesosphere and *E*-layer of the ionosphere [8]. Another discrepancy is the zonal number of disturbances (the number of waves that can be laid on the circumference along a chosen latitude). For example, according to theoretical consideration [11], the zonal number of quasi-2-day atmospheric mode $m = 3$, while the quasi-2-day disturbances of the plasma density in the *F*-layer of the ionosphere have $m = 1$ [5, 12].

The latter results were obtained using several ionosondes, which does not allow one to represent the global pattern of disturbances in the ionosphere in the range of planetary waves periods. The aim of this paper is a global investigation of the ionospheric disturbances in the above mentioned range of periods using the GPS satellites.

METHODS AND RESULTS

The data on the state of the ionosphere, derived by way of processing observations of the global positioning system (GPS), are in public access nowadays. After a complicated software processing the measurement data, obtained using 24 satellites and several hundred ground-based stations equipped with GPS receivers, come to world data centers (for example, http://sopac.ussd.edu and http://www.cx.unibe.ch/aiub/ gps.html) in streaming operation mode. There are several software packages that use the data from ground-based stations (so-called RINEX files), satellite ephemerides, and parameters of terrestrial, solar, and lunar orbits in order to calculate the absolute coordinates of these stations. The most perfect are the software developed in the Bern Institute of Astronomy (http://www. cx.unibe.ch/aiub/

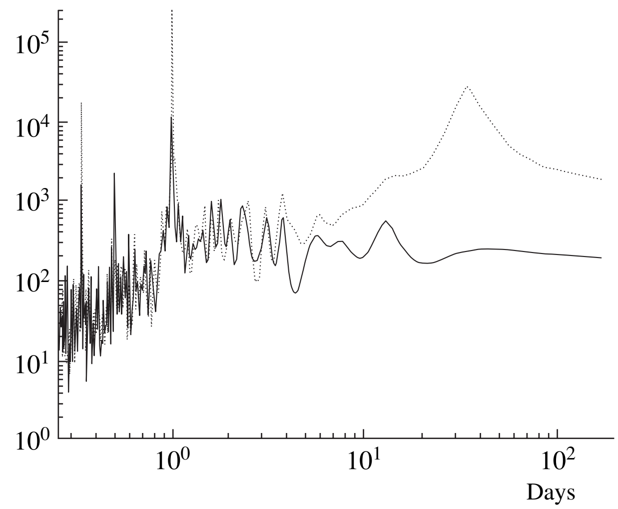

Fig. 1

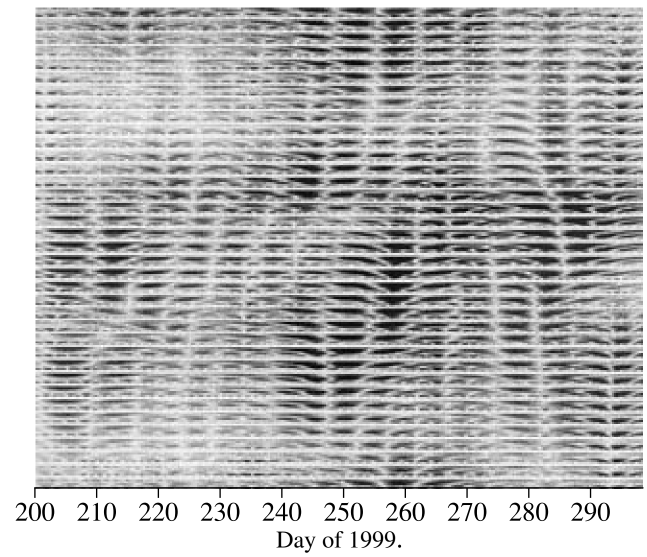

Fig. 2

bernese.html) and Massachusetts Technological Institute (http://www.gpsg.mit.edu/~simon/gtgk). For a high-precision positioning it is necessary to take into account that a distortion of radio signals due to irregularities of the ionosphere takes place when the signals propagate from satellites. In order to take this circumstance into account, an integral parameter is introduced, Total Electron Content (TEC) that characterizes the state of the ionosphere. The maps of TEC over the globe with a time interval of two hours are available on the site http://www.aiub.unibe.ch/ionosphere/. If variations of TEC are analyzed, for example, for a year one can find daily harmonics associated with the Earth's rotation about its axis, the component with a period of approximately 27 days and its harmonics and sub-harmonics (caused by the period of revolution of the Sun about its axis), and semi-annual cycles of TEC variations due to revolution of the Earth around the Sun. In order to investigate the TEC variations associated with propagation of planetary waves (in the period range 3 to 15 days), one can filter daily harmonics and sub-harmonics, but this cannot be done with sub-harmonics due to rotation of the Sun, since they fall into the range of periods under study.

For suppression of periodic fluctuations one can apply a rejector filter. The frequency response of a matrix rejector filter for suppression of waves with the wave vector $\mathbf{p}_r$ has the following form [13] $\mathbf{r}_r(f) = \mathbf{B}(f, \mathbf{p}_r)$, where $\mathbf{B}(f, \mathbf{p}_r) = \mathbf{I} - \mathbf{q}\mathbf{q}^*/(\mathbf{q}^*\mathbf{q})$, $\mathbf{q}(f, \mathbf{p}_r) = \exp(-i2\pi f\,\mathbf{p}_r^{\mathrm{T}}\mathbf{r}(j))$, $j = 1, \ldots, m$, m is the total number of observation points, $\mathbf{r}(j)$ are geographic coordinates of observation points, f is frequency, I is the unit matrix, and "*" and "T" are the symbols of complex conjugation and transposing, respectively.

Figure 1 shows the spectral densities of TEC global variations in the period from January 1 to December 31, 2001 for original (dashed line) and rejected (solid line) data. Here, the levels of original variations is considerably reduced in the period range 2 to 30 days. This is of special importance since these periods are close to the periods of planetary waves, and they cannot be excluded by filtration.

Next, the data from website http://www.aiub.unibe.ch/ionosphere are used for the analysis of TEC variations. These data represent the TEC values at points with a step of 5° in longitude and 2.5° in latitude following with an interval of 2 h. The time interval of 100 days was analyzed (Julian dates from 201 to 300 in 1999) at a fixed latitude 35° north and in the longitude interval from 180° west to 180° east. After rejector filtration of original data, low-frequency filtering was applied to eliminate components with periods of 2 days and less. Then, continuous wavelet analysis was performed in the range of periods from 2 to 15 days. The absolute values of coefficients of the Morlet continuous wavelet transformation were calculated. Figure 2 present the series of wavelets constructed using rejected and filtered data with a longitude step of 10° (each step is plotted along the vertical line) along 35° north latitude in the period range from 2 to 15 days. Light and dark regions in Fig. 2 correspond to low and high values of the wavelet coefficients. Since the absolute values are used, light and dark regions indicate to low and high amplitudes of original oscillations. It is convenient to use the light regions in order to construct the lines of phase synchronism in the selected space-time region. The analysis of this region shows that (i) there exist oscillations propagating both in eastern and in western directions; these movements are global, and sometimes they are observed throughout the entire latitude circle; (ii) some disturbances are almost immobile; and (iii) the velocity of propagation varies in absolute values from 0° to 36° per day.

Corresponding series of wavelets for the interval under analysis are shown in Figs. 3a and 3b for the period ranges from 2 to 4 days (quasi-2-day variations) and from 6 to 8 days (quasi-7-day variations). One should note here that the quai-7-day variations are selected in addition to the quasi-2-day variations not by chance. Westward propagating atmospheric planetary waves with a period of 6.5 days and zonal number m = 1 were interpreted [14] as a manifestation of instability in the mesosphere, more exactly, as a global response of the mesosphere to a certain unsteady source rather than simply quasi-5-day waves Doppler-shifted in frequency. It is interesting that quasi-7-day variations (but those in plasma density) are also present in the analyzed data (see Fig. 1).

Using the data of Fig. 3 one can estimate the zonal number of disturbances according to the formula $m = 2\pi R/\lambda = (360/T)/(\Delta\lambda/\Delta t)$, where R is the radius of latitude circle, λ is the wave length, T is the wave period, $\Delta\lambda$ is the longitude distance (in degrees), and Δt is the time interval. For practical calculation of the zonal number we make the following trick. We construct for various filtering channels the distribution functions of propagating disturbances depending on the parameter day/turnover (the number of days required for a wave to make a full revolution around the globe). Thus obtained histograms for quasi-7-day and quasi-2-day variations are presented in Figs. 4a and 4b. One can see in this figure that, independent of the direction of propagation (westward or eastward), the zonal number for quasi-7-day disturbances turns out to be of order of unity. It is surprising, however, that the zonal wave number of quasi-2-day variations (which propagate only westward) is also of the order of 1 instead of 3 (as it follows from theory [11]).

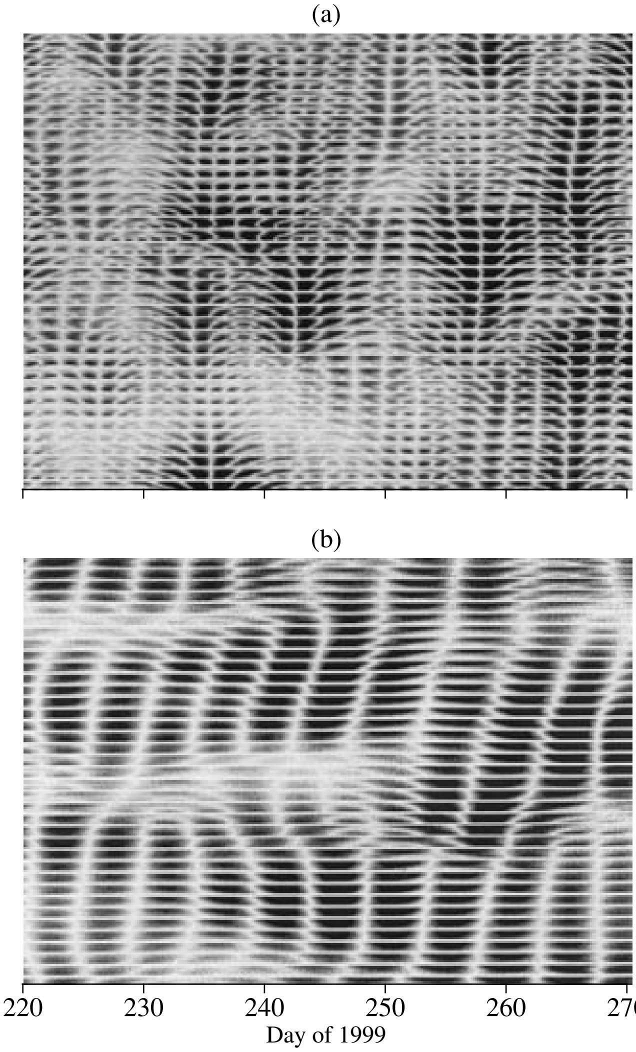

Fig. 3

DISCUSSION AND CONCLUSIONS

In [12], three types of quasi-2-day disturbances of the plasma density in the F-layer were found analyzing measurements of ionospheric parameter f_0F2 on several ionospheric stations in Europe over 11-year period: (i) propagating westward and having the zonal wave number m =1; (ii) steady-state oscillations with unknown wave number; (iii) oscillations classified as quasi-2-day variations but significantly changing the basic period when being detected at well separated stations. The latter type of oscillations has an atmospheric analog: at long-range bases the quasi-2-day oscillations of the wind in the atmosphere were detected, having similar phases and amplitudes, but different periods [15].

There is no commonly accepted point of view about the mechanism of disturbances of the first type. According to theoretical conceptions [11] the zonal number of quasy-2-day atmospheric mode is m = 3, while observed quasi-2-day disturbances of plasma density in the F-layer of the ionosphere have m = 1, as was demonstrated in this paper and in papers [5, 12]. In addition, quasi-2-day disturbances observed in variations of the f_0F2 parameter have a frequency maximum in the summer period and maximum amplitude takes place in the equinox [12]. At the same time, the maximum frequency of occurrence of atmospheric disturbances and their maximum amplitude fall on the local summer period.

One can assume that the interaction of quasi-2-day disturbances with sufficiently strong diurnal and semidiurnal tides (having m = 1 and m = 2, respectively) will lead to a change of the wave number. After all, unlike the planetary waves, tides are capable to propagate up to altitudes of the ionosphere. In this case, if quasi-2-day atmospheric waves modulate the tidal waves propagating upward, and the latter in turn excite the dynamo region of the ionosphere (E-layer), one can expect corresponding disturbances of plasma at altitudes of the F-layer. An experimental confirmation of

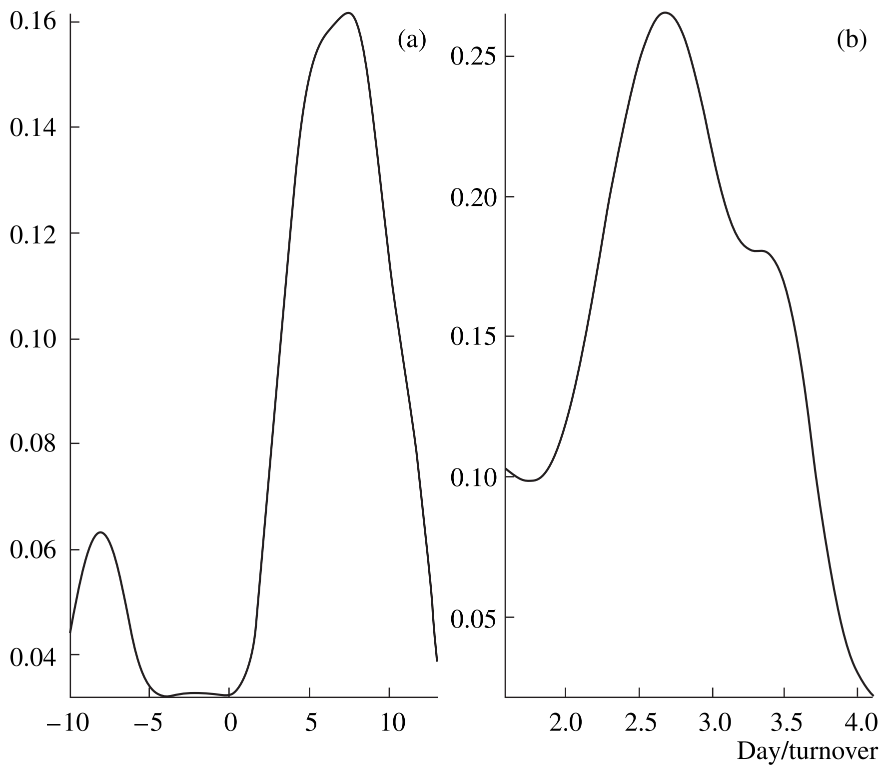

Fig. 4

this nonlinear mechanism of interaction between planetary waves and tides is given in paper [16].

It is possible also that normal modes in the thermosphere are distinct from those of the atmosphere [11], but no appropriate calculations have been done so far.

The results of the present work allow us to make more complete the knowledge about quasi-7-day variations. As was already noticed, the westward-propagating planetary waves with a period of 6.5 days and zonal number m = 1 were interpreted [14] as a global response of the mesosphere to a certain transient source. In the paper mentioned above the measurements of the wind velocity in summer and autumn periods of 1993 were analyzed using model approximations. It turned out that the same disturbances were studied also in [17, 18]. On the one hand, in the earlier paper [17] a westward-propagating wave was identified using wind measurements at middle latitudes. This wave appearing in a sufficiently wide latitude zone (±40°) had a period of 6–7 days and zonal number m = 1. On the other hand, radar measurements of mesospheric wind in the north-American sector isolated [18] a 7-day planetary wave propagating to the west with a velocity of about 20 m/s (this wave reached its highest intensity in the meridional component in the period from the middle of August to September). Finally, at the same period a 7-day modulation of the critical frequency of the sporadic E-layer (f_0E_s) was discovered [9] using measurements along a latitude chain of ionospheric stations, which testifies to an impact of a transient response of the mesosphere on the ionosphere plasma. The mechanism of influence is apparently similar to that described above for quasy-2-day waves. It is essential that the result of this work on mid-latitude 7-day variations of plasma (i) refer to another time interval and (ii) demonstrate that disturbances propagate both to the west and to the east. Therefore, transient global responses of the mesosphere and ionosphere seem to be more general phenomena than it was believed earlier.

Thus, the existence of ionospheric disturbances in the range of periods of planetary waves is established by analyzing global variations of TEC (total electron content) in the ionosphere in summer months of 1999 using GPS satellites. A substantial distinction of the structure of these disturbances (for quasi-2-day variations) from corresponding atmospheric waves is found. It is shown that ionospheric response in the range of quasi-7-day variations is more general phenomenon than it was thought before. The observed TEC variations are interpreted as a consequence of modulation of tides by planetary waves.

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