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Relative amplitude of the total electron content variations depending on geomagnetic activity

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Abstract

We developed a method of estimation of a relative amplitude dI/I of the total electron content (TEC) variations in the ionosphere as deduced from the data of the global GPS receivers network. To obtain statistically significant results we picked out three latitudinal belts provided in the Internet by the maximum number of GPS sites. They are high-latitudinal belt (50–80°N, 200–300°E; 59 sites), mid latitude belt (20–50°N, 200–300°E; 817 sites), and equatorial belt (±20°N, 0–360°E; 76 sites). The results of the analysis of the diurnal and latitudinal dependencies of dI/I and dI/I distribution probability for 52 days with different levels of geomagnetic activity are presented. It was found that on average the relative amplitude of the TEC variations varies within the range 0–10% proportionally to the value of the K_p geomagnetic index. In quiet conditions the relative amplitude dI/I of the TEC variations at night significantly exceeds the daytime relative amplitude. At high levels of magnetic field disturbances, the geomagnetic control of the amplitude of TEC variations at high and middle latitudes is much more significant than the regular diurnal variations. At the equatorial belt, on average, the amplitude of TEC variations in quiet and disturbed periods almost does not differ. The obtained results may be useful for development of the theory of ionospheric irregularities.

Keywords: Ionosphere; Total electron content; GPS; Relative amplitude

1. Introduction

Study of ionospheric plasma irregularities is one of the important problems of the Earth's physics and radiophysics. Ionospheric irregularities influence radio wave propagation within the broad radiowave range (Spoelstra and Kelder, 1984; Jacobson et al., 1995; Afraimovich et al., 1999).

The middle-scale and large-scale traveling ionospheric disturbances (MS TIDs or LS TIDs depending on the propagation velocity, from 100 to 1000 m/s) with a typical period of 20–60 min are an ionospheric response on acoustic-gravity waves (AGW) propagation (Hines, 1960; Hunsucker, 1982; Oliver et al., 1997; Afraimovich et al., 2000; Astafyeva et al., 2007). Intermediate-scale (IS) irregularities with a period of 2–10 min and horizontal dimensions of 10–30 km are usually associated with the spread-F phenomena (Bowman, 1992). IS irregularities are close by dimensions to small-scale irregularities causing the scattering of transionospheric signals (Yeh and Liu, 1982).

Recently a considerable progress has been achieved in the study of ionospheric irregularities using the new technology of GPS radio sounding (Davies and Hartmann, 1997). It allows us to obtain the data about variations of the total electron content (TEC) with high spatial and temporal resolution in various regions of the globe. Advancements in the development of this technology enabled to study of characteristics of wide range of the ionospheric irregularities as a function of local time, latitude, level of geomagnetic disturbance and other geophysical factors.

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The goal of this paper is a complex study of spatial and temporal characteristics of absolute (dI) and relative (dI/I) amplitudes of TEC variations under quiet and disturbed geomagnetic conditions.

2. Method of data processing

To study absolute and relative amplitude of TEC variations on various geophysical factors for the period from 1999 to 2005 we analyzed data for 12 quiet days (index $K_p < 3$) and 40 disturbed days ($K_p > 3$). The selected data cover mostly fall and spring equinox and a few winter days. To obtain statistically significant results we picked out three latitudinal belts with the maximum number of GPS sites presented in the Internet. They are high-latitude belt of North America (50–80°N, 200–300°E; 59 sites), mid latitude belt of North America (20–50°N, 200–300°E; 817 sites), and equatorial belt (−20 to 20°N, 0 to 360°E; 76 sites).

The standard GPS technology provides means for calculation of "slant" TEC I_S along line-of-sight (LOS) between GPS satellite and receiver based on phase measurements at each of spaced two-frequency GPS receivers. Data of phase measurements are contained in the RINEX-files, presented in the Internet (ftp://sopac.ucsd.edu/pub). A method of the TEC calculation was detailed and validated in a series of publications (e.g., Afraimovich et al., 2000).

To normalize the amplitude of TEC variations we converted "slant" TEC I_S to an equivalent "vertical" value I (Klobuchar, 1986):

$$I = I_S \times \cos\left[\arcsin\left(\frac{R_z}{R_z + h_{max}}\cos\theta_S\right)\right], \quad (1)$$

where R_z is the Earth's radius, $h_{max} = 300$ km is the height of the F2-layer maximum, θ_S is LOS elevation.

We selected continuous TEC series $I(t)$ which had a duration of about 2 h. So we had 22 overlapping time intervals for the day with a 1-h shift. We used specified threshold of 30° for elevations θ_S to the GPS satellites. $I(t)$ series for all GPS sites in the region under consideration and for all visible satellites were filtered in the time range of 20–60 min and 2–10 min using running average filtering. Then standard deviation σ of TEC variations was calculated for each filtered series. The σ values were averaged on all series; thus we got the mean absolute values $dI = [\sum \sigma_i]/m$, where $i = 1, 2, \ldots, m$; m is a total number of series for each 2-h time interval. The total number of analyzing series is about 10^6. The dI represents an absolute value of the amplitude of TEC variations.

The relative amplitude dI/I is determined by normalization of the standard deviation σ to the background I_0 value, where I_0 is the absolute vertical TEC obtained with 2-h time resolution from the global TEC maps in the IONEX format so called global ionospheric maps, GIM (Mannucci et al., 1998). The spatial range of GIM is 0–360° in longitude and −90° to 90° in latitude. The spatial resolution is restricted by the dimensions of an elementary GIM cell (5° and 2.5° in longitude and latitude, respectively). TEC estimation accuracy for each GIM cell is of about 10–20% (Mannucci et al., 1998). For the normalization, the I_0 values are used for the GIM cell closest to the GPS site used for determination of the standard deviation σ.

The series I, dI and dI/I were averaged over the chosen area to obtain the mean values of TEC $\langle I\rangle$, of the absolute amplitude $\langle dI\rangle$ and of the relative amplitude $\langle dI/I\rangle$ of TEC variations in the period rang of MS and IS ionospheric irregularities.

3. Diurnal dependence of the TEC variation amplitude

Now we consider in details the diurnal dependencies of the averaged values of TEC $\langle I\rangle$, of the relative $\langle dI/I\rangle$ and absolute $\langle dI\rangle$ amplitudes of the TEC variations for several chosen quiet and disturbed days. We start our analysis for the midlatitude ionosphere and then we will note features of the high-latitude and equatorial ionosphere.

To illustrate a typical diurnal dependence at middle latitudes we chose 2 days: moderately disturbed (quiet) day on November 3, 2003 and also the day on October 30, 2003 when a prominent magnetic storm was observed (Fig. 1, the right-hand and left-hand side, respectively). The geomagnetic activity indices D_{st} and K_p are shown in panels (d) and (h); the diurnal dependencies of averaged values of TEC $\langle I\rangle$ are shown in panels (a) and (e); the dependencies of the relative $\langle dI/I\rangle$ amplitude of the TEC variations are shown in panels (b) and (f), respectively. The same values for the absolute $\langle dI\rangle$ amplitude of the TEC variations are presented in panels (c) and (g), respectively. Data for MS and IS TEC variations are shown by thick and thin lines, respectively.

One can see in Fig. 1(e) smooth variation of $\langle I\rangle$ in quiet period with the TEC maximum around noon. This behavior is in general agreement with the regular TEC behavior obtained for a quiet period by the measurement of the angle of the polarization of the VHF signal of geostationary satellites (Davies, 1980; Afraimovich et al., 1999) and also by the two-frequency GPS measurements (Mannucci et al., 1998). The mean absolute amplitude $\langle dI\rangle$ of MS and IS TEC variations varies within 0.05–0.32 TECU (TECU $= 10^{16}$ m^{-2}) and 0.01–0.03 TECU, respectively, reaching maximum value also in the daytime (Fig. 1g).

However in disturbed conditions the character of TEC variations changes considerably. The value of the absolute amplitude $\langle dI\rangle$ increases by an order of magnitude (Fig. 1c), up to 3 TECU. At the same time the maximum shifts from the noon to the time moment of the maximum deviation of the D_{st} index during very high level $K_p = 9$. Nevertheless, the maximum values of $\langle dI\rangle$ are observed mainly in the daytime.

The diurnal behavior of the relative amplitude $\langle dI/I\rangle$ differs cardinally from the corresponding dependence of $\langle dI\rangle$. That distinction manifests in quiet conditions most significantly: the maximum values for $\langle dI/I\rangle$ for MS and IS TEC variations are observed at night, not in the daytime.

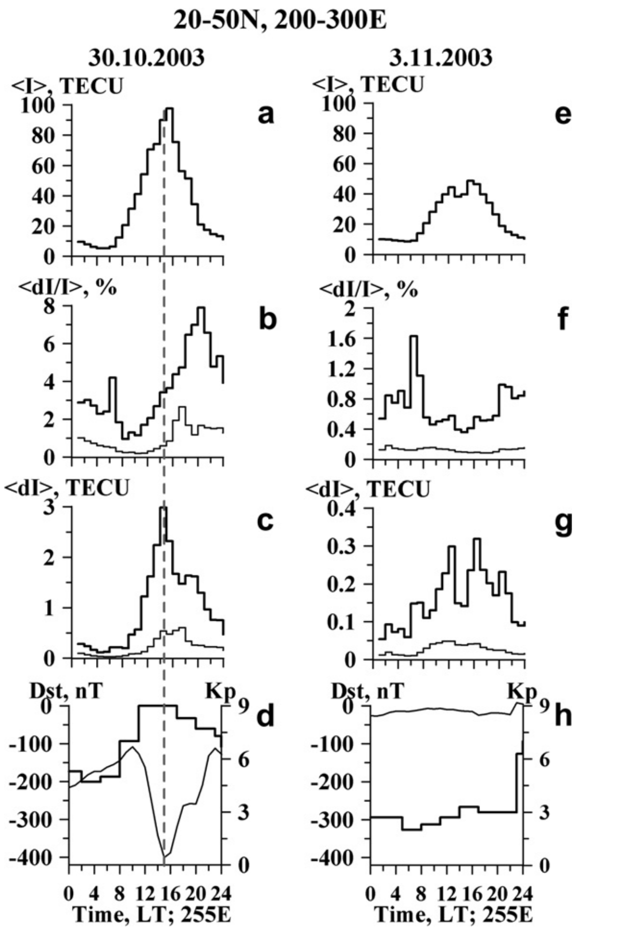

Fig. 1. (d, h) Indices of geomagnetic activity D_{st} and K_p; diurnal dependencies (a, e) of the averaged values of TEC ($\langle I \rangle$), (b, f) of relative ($\langle dI/I \rangle$), and (c, g) of absolute ($\langle dI \rangle$) amplitude MS (thick lines) and IS (thin lines) TEC variations during the magnetic storm on 30 October 2003 and quiet day on 3 November 2003. Middle latitudes.

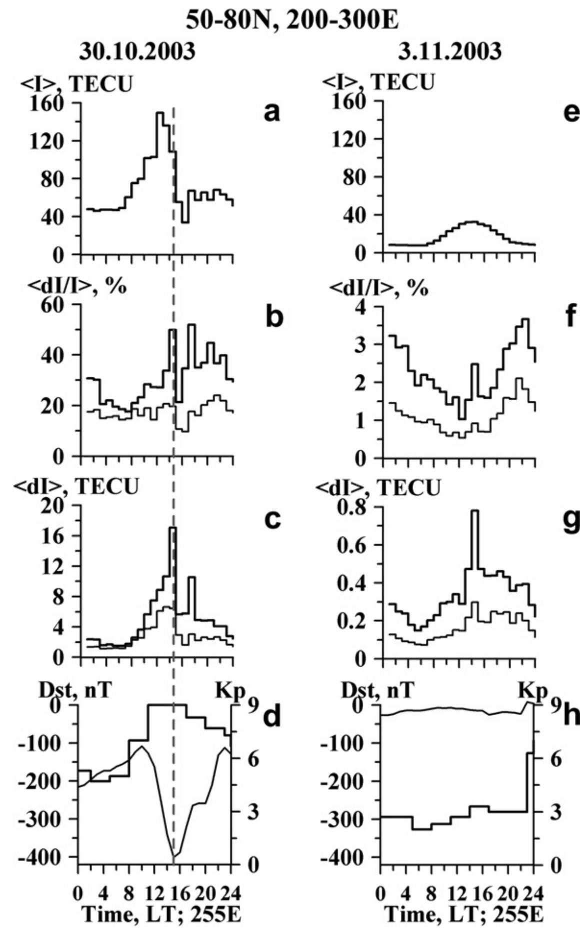

Fig. 2. Same as in Fig. 1, but for high latitudes.

In disturbed conditions the changes in $\langle dI/I \rangle$ are governed not only by diurnal behavior, but by the magnetic field variations as well. The vertical dotted line in Fig. 1 (at the left) marks the moment of a sharp increase of the absolute amplitude $\langle dI \rangle$ of the TEC variations on October 30, 2003, when the value of $\langle dI \rangle$ reached 3 TECU. This example shows that the geomagnetic control of the amplitude of the TEC variations during strong disturbances of the geomagnetic filed appears more significant than the regular diurnal variations.

At high latitudes (Fig. 2) the diurnal dependence of TEC $\langle I \rangle$ and its variations in quiet conditions differ from the midlatitude conditions. First of all it has higher amplitude; the absolute and relative amplitudes $\langle dI \rangle$ and $\langle dI/I \rangle$ during the main phase of the magnetic storm on 30 October 2003 reaches 16 TECU and 50%, respectively.

Moreover, one can notice a difference in amplitudes $\langle dI \rangle$ and $\langle dI/I \rangle$ of TEC variations for ionospheric irregularities of different scales (not more than by a factor of 2 and by an order of magnitude at high and middle latitudes, respectively). This fact indicates that there is a cardinal decrease in the declination of the power spectrum of TEC disturbances due to the increase in the amplitude of the small-scale part of the spectrum (Afraimovich et al., 2001).

Even more astonishing this difference of middle latitudes is observed at the equatorial latitudes (Fig. 3). In order to estimate the mean TEC response on magnetic storm variations independently of longitude we accumulated for all longitudes from 0 to 360E and used UT scale on Fig. 3. First of all, in disturbed conditions an increase in the relative and absolute amplitudes of TEC variations as compared to quiet conditions is insignificant. The maximum value of the relative amplitude $\langle dI/I \rangle$ is systematically observed at night. This regularity is not broken even during the main phase of the magnetic storm. This conclusion agrees completely with the widely known morphology of ionospheric scintillations at equatorial latitudes based on numerous measurements by different techniques of ionospheric sounding (Aarons, 1982; Yeh and Liu, 1982).

For the quiet days the above-mentioned latitudinal dependencies are distinct at daily mean dependencies. We used the data averaged for 12 quiet days ($K_p < 3$) for more exact estimation of diurnal dependencies because it determined only LT, but UT. Fig. 4 shows diurnal dependencies of the averaged values of the absolute $\langle dI \rangle$ (at the left) and relative $\langle dI/I \rangle$ (at the right) amplitudes of IS (thin lines) and

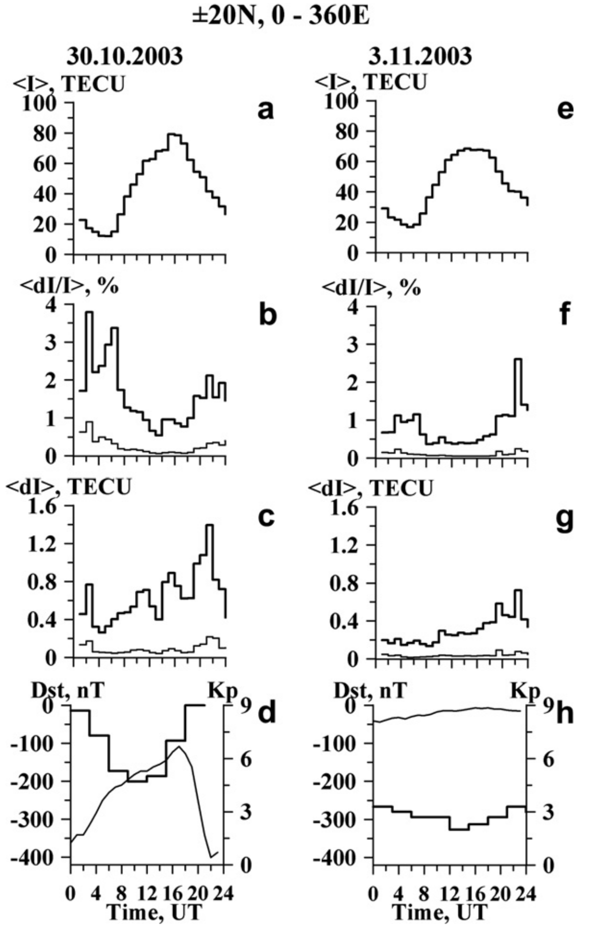

Fig. 3. Same as in Fig. 1, but for equatorial latitudes.

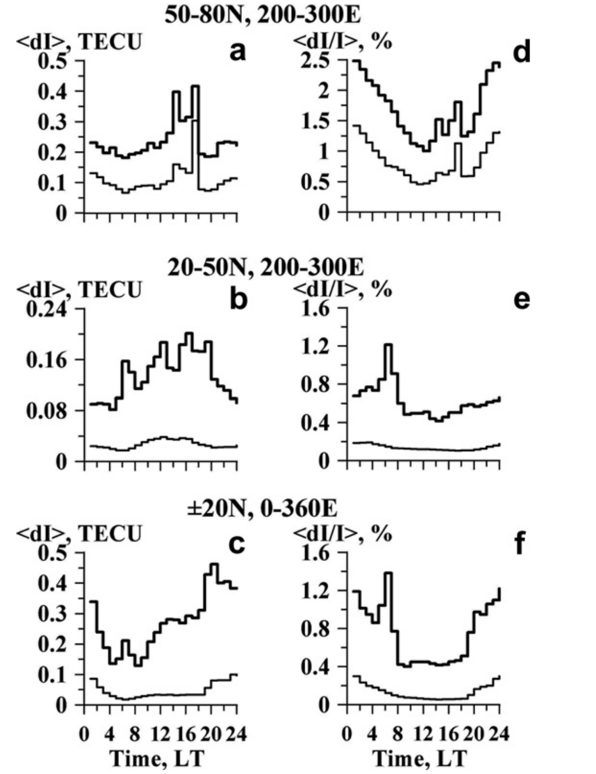

Fig. 4. Total diurnal dependencies of the averaged values of the absolute $\langle dI \rangle$ (left) and relative $\langle dI/I \rangle$ (right) amplitudes of MS (thick lines) and IS (thin lines) variations of TEC for 12 quiet days ($K_p < 3$); a, d – high latitudes; b, e – middle latitudes; c, f – equatorial latitudes.

MS (thick lines) TEC variations: (a, d), (b, e), and (c, f) correspond to high, middle and equatorial latitudes, respectively. One can see in Fig. 4 that the maximum values of the relative amplitude of the TEC $\langle dI/I \rangle$ variations are observed substantially at night.

In quiet conditions the relative amplitude of the TEC variations at night exceeds considerably the daytime values by a factor of 3–5 at the equatorial and high latitudes and of 2 at middle latitudes, respectively. During high level of magnetic field disturbance, the geomagnetic control of the amplitude of TEC variations is even more significant than the regular diurnal variations.

4. Distribution of the probability of the relative amplitude of TEC variations and dependence on the K_p index

The statistical characteristics of the relative amplitude of TEC variations are very important for development of ionospheric irregularities generation mechanisms and for estimations of transionospheric radio signal distortions (Afraimovich and Karachenschev, 2003).

Fig. 5 shows the approximation of the normalized distributions $P(\langle dI/I \rangle)$ of the relative amplitude $\langle dI/I \rangle$ of TEC variations in quiet (gray line, index 1) and disturbed (black line, index 2) conditions. $P(\langle dI/I \rangle)$ for MS and IS ionospheric irregularities are shown on left and on right sides in Fig. 5: (a, d), (b, e), and (c, f) correspond to high, middle and equatorial latitudes, respectively. The total amount of 2-h averaging over the entire area of the North America was 288 and 936 for quiet and disturbed periods, respectively. The most probable values of $\langle dI/I \rangle$ in quiet (X_1) and disturbed (X_2) conditions are shown on each panel.

One can see from Fig. 5 that at high latitudes in quiet periods the relative amplitude of MS disturbances does not exceed 4–5%, whereas in disturbed periods it may reach 10–12%. Similar dependence is also observed for IS variations of TEC with the only difference that the general disturbance level is less than for MS by a factor of 4–5. At middle latitudes this dependence on the level of geomagnetic disturbance remains the same. However on the whole the amplitude of the MS and IS disturbances decreases by a factor of 2–3 and 5, respectively. At the equatorial latitudes, on average the amplitudes of MS and IS variations in quiet and disturbed periods almost do not differ.

The difference of the dependencies of the TEC relative amplitude on the geomagnetic disturbance level at various latitudes in the best way is illustrated in the regression dependencies of the amplitude of TEC variations on the values of the K_p index shown in Fig. 6. Points show the values of $\langle dI/I \rangle$ averaged over 3 h and thick line shows the approximating lines: left side – MS ionospheric irregulari-

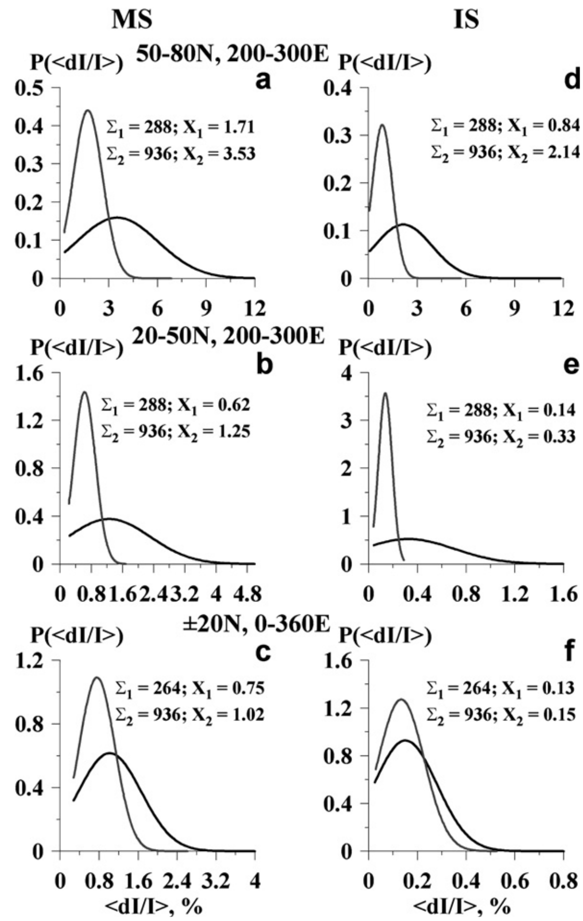

Fig. 5. Approximation of the total normalized distributions **P(⟨dI/I⟩)** of the relative amplitude of TEC variations for quiet (gray line) and disturbed (black line) conditions: (left) MS and (right) IS variations; a, d – high latitudes; b, e – middle latitudes; c, f – equatorial latitudes.

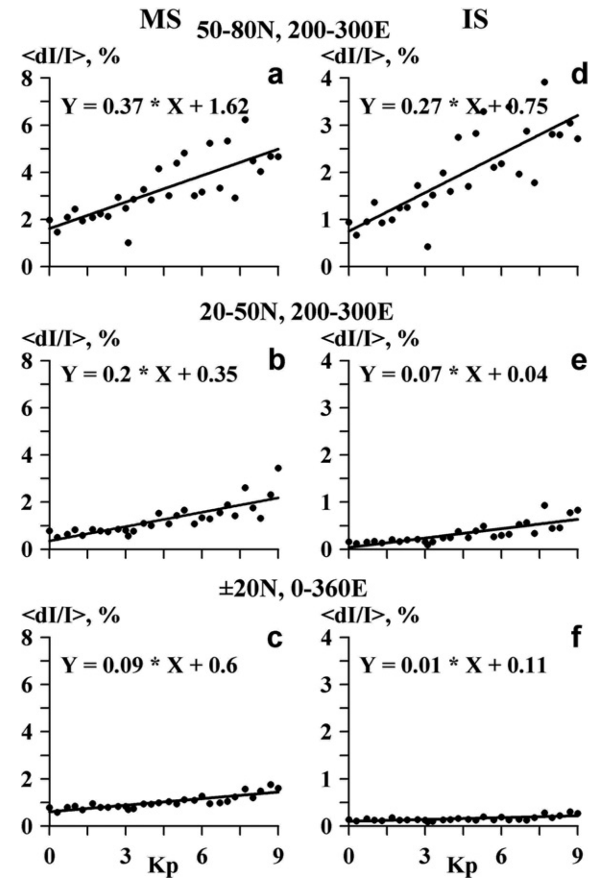

Fig. 6. Regression dependencies of the amplitude of TEC variations on K_p index. Points show the averaged over 3-h interval values of ⟨*dI*/*I*⟩; thick lines show approximating lines. (left) MS and (right) IS variations; a, d – high latitudes; b, e – middle latitudes; c, f – equatorial latitudes.

ties; right side – IS ionospheric irregularities; (a, d), (b, e) and (c, f) correspond to high, middle, and the equatorial latitudes, respectively.

On average, the relative amplitude of TEC variations is proportional to the value of the geomagnetic K_p index. This dependence is distinct at high latitudes (the proportionality coefficient $k = 0.37$), it is weaker at middle latitudes ($k = 0.2$) and the weakest at the equator ($k < 0.1$).

5. Discussion and conclusion

It was found that on average the relative amplitude of the TEC variations varies within the range 0–10% proportionally to the value of the K_p geomagnetic index. In quiet conditions the relative amplitude dI/I of the TEC variations at night significantly exceeds the daytime relative amplitude. At high levels of magnetic field disturbances, the geomagnetic control of the amplitude of TEC variations at high and middle latitudes is much more significant than the regular diurnal variations. At the equatorial belt, on average, the amplitude of TEC variations in quiet and disturbed periods almost does not differ. The obtained results may be useful for the development of the theory of ionospheric irregularities.

Our data agree with the results of measurements of the absolute amplitude ⟨*dI*⟩ of TEC variations obtained at transionospheric VHF sounding by a signal of geostationary satellite ETS-2 (Afraimovich et al., 1999) and also with the data of the analysis of the variation of spectra of TEC according to the GPS data (Afraimovich et al., 2001). Unexpected inverse dependence of the TEC variation was found for quiet period: the maximum values of ⟨*dI*/*I*⟩ are observed by night, but not in the daytime. The latter means that the mechanisms of generation and propagation of AGW differ significantly in the daytime and at night.

This result is in agreement with conclusions of other researches. Based on the data of TEC measurements in Los Alamos (35.9N, 106.3W), Jacobson et al. (1995) claimed that the seasonal variations in MS TID occurrence and propagation direction are different in the daytime and at night. They showed that the daytime MS TID is formed mainly during the winter solstice and propagates southward, whereas the night-time MS TID occurs mainly during the summer solstice till the fall equinox and propagate northwestward.

Kelley and Miller (1997) noted that the difference between the direction of MS TID propagation in the daytime and at night is responsible for the difference in MS TID generation. The amplitude of gravity waves grows at a depletion of the neutral density; see, for example, (Hines, 1960). Larger amplitude of gravity waves is able to generate larger disturbances in the plasma density, i.e., in the MS TID activity. On the other hand, the rate of the linear growth of the Perkins instability is also the inversely proportional to the neutral density (Perkins, 1973). Most likely the Perkins instability is a source of night-time MS TID though the rate of the linear grow is very small.

Authors of (Tsugawa et al., 2004; Kotake et al., 2006) found also that MS TID activity in the daytime differs from one at night. It depends on the season, solar activity, latitude and longitude. The activity of daytime MS TID is high in winter. In the Japanese and Australian longitudinal sector, nighttime MS TID are most active near the June solstice, whereas it is most active near the December solstice in the European longitudinal sector. Nighttime MS TID activity at the Japanese and Australian longitudinal sector shows negative correlation with solar activity, whereas solar activity dependence is not seen in daytime MS TID activity. These results suggest that mechanisms causing MS TID could be different between daytime and nighttime.

The results shown in (Hernandez-Pajares et al., 2006): downward propagation, productivity correlated to magnetic field, compatibility to neutral atmospheric periods, Coriolis effect traces, are compatible with the initial assumption of AGW as the main origin of the studied MSTIDs. The MSTIDs which occur at daytime in local winter and at nighttime in local summer are associated with the solar terminator and modulated by the solar cycle. The corresponding periods are compatible (higher) with the theoretical prediction, which is given by the neutral atmosphere buoyancy period associated with the Brunt-Vaisala frequency (about 600 s). Moreover, higher TIDs productivity is mainly associated with the downward vertical propagation.

Under the averaging of TEC variation amplitude, the main contribution brings the midlatitude belt of GPS sites. This belt is located at a distance of about 2000 km from the southern boundary of the auroral source of TIDs occurred during geomagnetic disturbances. That TIDs move equatorward with the velocity of about 300–1000 m s^{-1} (Hunsucker, 1982; Afraimovich et al., 2001; Astafyeva et al., 2007). Therefore mean delay between significant alterations of geomagnetic field intensity during geomagnetic storms on October 30, 2003 and the relative amplitude $\langle dI/I \rangle$ increasing is of about 2.0 h.

However, there is a large evidence of other mechanisms of TIDs which could have the same observational features. For instance, Foster and Rideout (2005) have shown that for the same storm discussed in our paper (October 30, 2003) TEC increase is observed at post-noon local times and associated with sub-auroral electric fields.

There is a different mechanism of generation of small scale irregularities during the major magnetic storms. By using data from GPS receivers global network Astafyeva et al. (2007) detected huge-amplitude solitary large-scale traveling AGWs which manifested themselves as perturbations of TEC of duration of about 40 min. LS disturbances originated in the auroral area after significant alterations of geomagnetic field intensity during geomagnetic storms on October 29–30, 2003, propagated with velocity about 1000–1200 m/s, and caused generation of secondary small-scale waves with time period of 2–10 min. Such structure followed the solitary intensive AGW at a distance more than 4000 km within the territory with high values of “vertical” TEC and steep gradients of TEC.

Detailed analysis of space-temporal properties and nature of MS and IS TEC variations is a very difficult issue, and it is out of the scope of this paper.

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