THREE-DIMENSIONAL STRUCTURE OF THE IONOSPHERIC ELECTRON DENSITY DISTURBANCES CREATED BY THE VERTICAL ELECTRIC CURRENTS FLOWING BETWEEN THE EARTH AND THE IONOSPHERE

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Abstract. The ionospheric and plasmospheric electron density disturbances created by the vertical electric currents flowing between the Earth and the ionosphere have been simulated using global numerical Upper Atmosphere Model (UAM). The calculated three-dimensional structure of the ionospheric electron density disturbances demonstrates importance not only vertical component of the F2-region ionospheric plasma drift in producing NmF2 and total electron content (TEC) disturbances but also meridional and zonal plasma drift movements. The calculated TEC disturbances are discussed in relation with the features of the TEC anomalies observed before strong earthquakes. Reality of the vertical electric currents with the density of $10^{-8}$ A/m$^2$ required for producing TEC disturbances of magnitude 30-50% relative to quiet conditions is also discussed.

Introduction

The anomalous Total Electron Content (TEC) disturbances observed before strong earthquakes are often reported by numerous investigators after processing GPS data (Liu et al., 2004; Pulinets and Boyarchuk, 2004; Zakharenkova et al., 2006, 2007). These anomalies are strong long-living positive and negative disturbances (up to 90% relative to the non-disturbed values) that occupy area up to 1500 km along geomagnetic meridian and 3000-4000 km along geomagnetic parallel. They are linked to the earthquake epicenter but appear not exactly above it. TEC disturbances are often reported at the magnetically conjugated to the epicenter areas. Anomalies are rather stable and do not propagate away from the epicenter. These disturbances are treated as the ionospheric earthquake precursors.

It has been discovered that TEC disturbances prior to Haiti earthquake (January, 2010) depressed (almost disappeared) with the sunrise terminator income and restored with the sunset terminator leaving the near-epicenter region (Zolotov et al., 2011). These features were confirmed after processing GPS data for days preceding to Japan (March, 2011), Turkey (October, 2011) and Chile & Argentina (January, 2011) earthquakes (Zolotov et al., 2012). Finally, analysis of TEC disturbances preceding to over 50 seismic events during 2005-2006 mostly confirmed relation with the sunlit ionosphere income and leaving (Romanovskaya et al., 2012, Namgaladze et al., 2012). According to Romanovskaya the day-time TEC disturbances were revealed only in 20% of investigated events. Statistical data analysis also reported effects in TEC at both epicenter and magnetically conjugated areas in 65% of events.

We consider the electromagnetic drift of the F2-layer ionospheric plasma under action of the seismogenic electric field as the most probable cause that produces the pre-earthquake TEC anomalies (Namgaladze and Zolotov, 2012 in this issue and references in it). This hypothesis is strongly supported by localization of the disturbances near epicenter and magnetically conjugated areas. It should be mentioned that TEC disturbances related with magnetic activity propagate away from the source. As they cannot be localized at the limited area we do not consider neutral atmosphere variations as the physical mechanism that could explain observed pre-earthquake TEC disturbances.

Seismogenic electric fields can be created by the additional vertical electric currents flowing between the earthquake epicenter and the ionosphere. The “positive holes” activated during rock stress (Freund, 2011) or seismic-related radioactive species’ emanation (Pulinets and Boyarchuk, 2004) could be considered as the air ionization and vertical electric currents’ sources.

In this study we present spatio-temporal variations of the electron number density and TEC disturbances created by the external electric currents of seismogenic origin using the Upper Atmosphere Model (UAM). We compare the model results with the above mentioned features of the TEC disturbances.
observed before the strong earthquakes and discuss them in terms of the proposed physical mechanism of the phenomena.

Methods

The simulations of the TEC variations were executed using the Upper Atmosphere Model (UAM). It is a three-dimensional global numerical model that describes the mesosphere, thermosphere, ionosphere, plasmasphere and inner magnetosphere as a whole system by solving continuity, momentum and heat balance equations for neutral and charged components as well as equation for the electric potential.

Firstly, we calculated concentrations, temperatures and velocities for the neutral and charged particles as well as electric fields’ values to obtain parameters for the quite conditions. Then sources of the additional seismogenic electric current with density of about $20-10^9$ A/m$^2$ were switched on at the area of about 200 km along magnetic meridian and 2500 km along magnetic parallel at the height of 80 km to calculate the same parameters for disturbed conditions.

According to (Sorokin et al., 2007) the external current density of about $10^6$ A/m$^2$ at the area of about 200 km in radius is required to create the electric field of about several mV/m in the ionosphere. In turn, such fields are able to disturb TEC up to 50 % and more (Kuo et al., 2011; Karpov et al., 2012; Namgaladze et al., 2013 and references in it). The density used in our calculations is much less than estimations by Sorokin, but it is 10000 times larger than regular values ($2\cdot10^{-12}$ A/m$^2$) of the “fair weather” electric current density (Rycroft et al., 2000). Nevertheless there are some observations and experiments that report existence of such anomalous values. For example, electric currents with the density of about $10^6$ A/m$^2$ and $10^8$ A/m$^2$ were registered during measurements under small Florida thunder-storm for a short period of time (Krider and Musser, 1982) and over thunderstorms at the height of about 20 km (Blakeslee et al., 1989) respectively. Typical electric current with density of about $5\cdot10^6$ A/m$^2$ flowed through the average cross section of poplar tree (Le Mouel et al., 2010). Finally, the density of about $10^6$ A/m$^2$ was registered during laboratory experiments with stressed rocks (Freund, 2011).

Electromagnetic plasma drift components

Let us consider spatio-temporal variations of the calculated electron density and TEC disturbances for the case with seismic currents acting along 30° mag. lat. and directed to the Earth (downwards).
As it has been noticed earlier we consider the electromagnetic drift of the F2-layer ionospheric plasma as the main reason in producing the pre-earthquake TEC anomalies. The drift is caused by action of the seismogenic electric fields which in turn are created by the electric currents flowing between the earthquake fault region and ionosphere. Stability of the observed anomalies, their localization near both epicenter and magnetically conjugated area could be explained only by the plasma drift under action of the electric fields. The disturbances are not related with neutral atmosphere modifications, because if they are, they should propagate from the source.

In the middle latitudes the upward component of the \([\mathbf{E} \times \mathbf{B}]\) drift created by the eastward electric field leads to the increase of the NmF2 and TEC due to the plasma transportation to the regions with lower concentration of the neutral molecules (with lower loss rate of dominating ions O\(^+\) in the ion-molecular reactions). The westward electric field leads to the opposite effect in the NmF2 and TEC. In the equator area the eastward electric field causes the deepening of the Appleton anomaly minimum due to intensification of the fountain-effect.

Actual plasma movements under action of seismogenic electric fields are much more complicated. The UAM calculated electric potential differences relatively to the non-disturbed conditions for the considered configuration are presented in Fig. 1. The disturbed electric fields are directed perpendicularly to the electric potential isolines and plasma moves in direction perpendicular both to the electric and magnetic fields. As one can see in Fig. 2 the zonal electric field at the epicenter meridian equals zero (only the meridional component of the field presents). For this reason there is no vertical plasma drift at the epicenter meridian at all, while the vertical component of the plasma drift directed downwards at the western meridians and upwards at the eastern meridians relatively to the epicenter meridian for the case with the seismic electric currents flowing downwards.

Fig. 2 shows the horizontal components of the plasma drift also playing important role in producing TEC disturbances additionally to vertical one. Meridional components of the plasma drift are directed from the equator at the area to the east from the epicenter meridian and towards the equator at the area to the west from epicenter. Zonal components at the area between the epicenter and magnetically conjugated parallel are directed to the east. Zonal components at areas to the north from epicenter and to the south from magnetically conjugated point are directed to the west. Seismic electric currents of opposite direction (from the Earth) lead to the opposite directions of \(\mathbf{E}\), vertical, zonal and meridional drift components.

![Fig. 3](image-url)

Fig. 3. Altitude-latitude cross sections of the calculated electron number density’ logarithm at 23:00 LT along the epicentre meridian (central column) and 15° to the west and to the east (left and right columns respectively). Top row: quiet conditions, middle row: disturbed conditions for the case with the seismic currents flowing to the Earth, bottom row: disturbance. The star denotes the epicentre, the abscissa axis – geomagnetic latitude (deg.), the ordinate axis – altitude (km).
A joint action of the vertical, zonal and meridional drift components leads to the complicated plasma movement. Calculations of electron density using UAM illustrate this physical process in Fig. 3 (see also, Karpov et al., 2012b, Namgaladze et al., 2012) where altitude-latitude cross sections along the epicenter meridian (central column) and along the meridians 15° to the west and to the east (left and right columns respectively) are presented for the case with seismic currents flowing to the Earth. As one can see, the action of the seismic electric currents causes insignificantly changes or slight decrease of HmF2, while NmF2 changed dramatically (compare top and middle rows in Fig. 3).

UAM calculated TEC disturbances’ response on different input current parameters

The UAM calculations (Karpov et al., 2012a, Namgaladze et al., 2012; Namgaladze et al., 2013) have shown that the described above sources of the electric currents produce TEC disturbances similar to the observed pre-earthquake anomalies (see Fig. 4). The stability of the anomalies, localization near both epicenter and magnetically conjugated area, asymmetry relative to the magnetic equator and response on sunlit ionosphere’ income and leaving were reproduced. Asymmetry of the disturbances relative to geomagnetic equator is explained by different ionospheric conditions in northern (winter) and southern (summer) hemispheres as it clearly can be seen in Fig. 1 (top row).

It also has been shown that strongest disturbances were created by the sources located at 30° and 45° mag. latitude in comparison with the sources at 5° and 15° mag. lat. (see different columns in Fig. 4). By change direction of the seismic currents (to the ionosphere or to the Earth) the positive and negative disturbances took the place of each other, i.e. they redistributed relatively to the geomagnetic meridian crossing the epicenter and magnetically conjugated point (see Fig. 4A and Fig. 4C).

We also considered configurations with seismic electric currents and “back” currents acting simultaneously. The “back” currents compensate seismic currents in order to keep total current in global electric circuit constant. Two different configurations were investigated. In first configuration “back” currents were switched on at the nodes of the numerical grid adjacent to the nodes with seismic currents. In second configuration “back” currents were spread out all over the globe (excluding the nodes with seismic currents). By comparison between these...
configurations we concluded that first one produces TEC disturbances that are weaker by magnitude and occupy smaller area (see Fig. 4D). The second configuration produces very similar disturbances as the configuration without any “back” currents (see Fig. 4A and Fig. 4B).

Simulations using external electric currents of seismogenic origin as a model input have been also performed using the SAMI2 model (Kuo et al., 2011). The difference is that their currents flowed over the area of 200 by 30 km that is much smaller than in our case. Seismic currents (without any currents of opposite direction) were switched on near ground surface (not at the height of 80 km as in our case). Then they used the empirical model of the atmosphere's conductivity based on physical mechanism of air ionization by positive holes activated during rock stress (Freund, 2011). They simulated only TEC response at the epicenter region and did not consider magnetically conjugated one. The simulations were local (not for the globe as in our case). According to their simulations the current density of 0.2-10 μA/m² in the earthquake fault zone can cause TEC variations of up to 2-25 % in the day-time ionosphere and the density of 0.01-1 μA/m² can lead to the night-time TEC variations of 1-30 %. Such huge currents are required due to a too small area of the current generation in their simulation. Beside of this, our and their model results do not contradict each other.

Conclusions

Thus, according to simulations using UAM seismogenic sources of the electric currents with the density of about 20·10⁻⁹ A/m² switched on at the area of about 200 by 2500 km at the height of 80 km produce TEC disturbances similar to pre-earthquake anomalies. Simulated disturbances with magnitude up to 50 % occupy area of about 1000 by 4000 km. They are stable and linked both to the epicenter and magnetically conjugated area. They do not propagate from the source like disturbances caused by neutral atmosphere’ variations due to magnetic activity. The modeled disturbances disappear with well-conducted sunlit ionosphere’s approach and restore after the sunset terminator income. The asymmetry of the anomalies relatively to the magnetic equator is explained by the different ionospheric conditions in the summer and winter Hemispheres.

The density of the simulated electric currents is 10000 times larger than regular “fair weather” currents’ density, but series of measurements during observations and laboratory experiments confirm the existence of such anomalous currents in nature.

The calculated variations of the electron number density show importance of the meridional and zonal components of the electromagnetic drift which redistribute ionospheric plasma along meridian and parallel respectively. The vertical component of the drift moves plasma upwards (downwards) and downwards (upwards) at the areas to the west and to the east from the epicenter meridian respectively in the case of the seismic currents flowing downwards (upwards). We expect all three components playing an important role in producing TEC disturbances prior to the strong earthquakes.

The strongest TEC disturbances were obtained for the sources located at 30° and 45° mag. lat. The currents’ direction change caused the mirror reverse of the positive and negative disturbances relatively to the magnetic meridian crossing epicenter and magnetically conjugated point. The configurations with the “back” currents switched on all over the globe produce anomalies very similar to those created by the configurations with only “direct” seismogenic currents. Configurations with “back” currents switched on only at the grid nodes adjacent to the nodes with seismogenic currents produce the TEC disturbances that occupy smaller area and are weaker by magnitude.

References


