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COMPARISON OF THE IONOSPHERIC EFFECTS OF THE SPACE WEATHER AND SEISMOGENIC DISTURBANCES

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Abstract. The ionosphere variations before M6.7 earthquake in India on January 3, 2016 have been analyzed. The earthquake has occurred after the series of magnetic substorms on December 31, 2015 and January 1, 2016. The relative total electron content (TEC) disturbances have been estimated using the global maps of the total electron content (GIM-TEC) and calculated numerically using the 3D global first-principle Upper Atmosphere Model (UAM) for the whole period including the days before, during and after the substorms. Numerical simulations were repeated with the seismogenic vertical electric currents switched on at the earthquake epicenter. The UAM calculations have reproduced general behavior of the ionosphere after the main phase of the geomagnetic storm on January 1, 2016 in the form of negative TEC disturbances propagating from high latitudes, especially strong in the Southern (summer condition) hemisphere. It was shown that the local ionospheric effects of seismic origin can be identified on the background of the global geomagnetic disturbances. These seismo-ionospheric effects are visible as the nighttime regions with the additional negative TEC disturbances extending from the Eastern side of the epicenter meridian to the Western side, both in the observations and simulations. It was found that the vertical electric field and corresponding westward electromagnetic drift play a decisive role in the formation of the ionospheric precursors of this earthquake.

Introduction

The ionosphere response to the seismic activity has been the subject of the numerous studies aiming at detection of the ionospheric precursors of earthquakes. One of the ionosphere parameters often used to study the ionosphere response to the earthquakes preparations is the TEC (total electron content) of the ionosphere obtained via the global position systems (GPS, GLONASS). The formation of the pre-seismic TEC disturbances was explained by the vertical electromagnetic [$\boldsymbol{E}$ x $\boldsymbol{B}$] drift of the F2-layer plasma under the action of the electric field generated in the ionosphere above the epicenter region (*Namgaladze et al*., 2009). The abnormal electric fields with the intensity of several mV/m were detected by DEMETER above the regions with the enhanced seismic activity (*Zhang et al*., 2014). *Sorokin & Hayakwa* (2013) and *Namgaladze & Karpov* (2015) considered these electric field as a result of the vertical electric current generated over the tectonic fault due to the separation and vertical transport of the opposite charges driven by the non-electric forces, similar to the thunderstorm currents charging the ionosphere. The numerical simulations with the Upper Atmosphere Model (UAM) have shown that the vertical electric current of ~20 nA/m^2 is required to generate the local pre-seismic electric fields of several mV/m and create the TEC disturbances analogous to the observed ones (*Namgaladze et al*., 2013; *Karpov et al.*, 2013).

The global state of the ionosphere is affected by numerous influences including the solar and geomagnetic activities, meteorological events and anthropogenic sources. It also experiences normal seasonal, day-to-day and diurnal variations. Thus, it is very important to clearly identify the ionospheric disturbances associated with the seismic activity and separate them from the regular Space weather variations. Most, if not all, case studies and statistical analysis were conducted for the periods of the low solar and geomagnetic activities. In this study we analyze the ionosphere behavior for the period of high geomagnetic activity in December 2015 and January 2016 followed by M6.7 earthquake in India on January 3, 2016. Here we try to distinguish the pre-seismic TEC variations from the effects of the magnetic storm using the GPS observations and the UAM numerical calculations.

Methods

M6.7 earthquake occurred at 23:05:22 UTC on January 3rd, 2016 with the epicenter 30km W of Imphal, India (24.804°N, 93.651°E). The geomagnetic conditions for the period before the earthquake are characterized by the two series of substorms on December 20–21 and December 31–January 1 with Kp≥6 and Dst reaching –150nT and –100nT, respectively. We used the global ionospheric maps of the TEC (GIM-TEC) to estimate the TEC disturbances relative to the quiet values for this period. In order to obtain the background values and exclude the disturbed TEC values due to the high geomagnetic activity, we have averaged the TEC for December 25–30. During this period Kp<3 most of the time, exceeding 4 once on December 26, and Dst has never changed more than 30 nT within a day.

For numerical calculations of the TEC variations we use the three-dimensional global first-principle Upper Atmosphere Model (UAM) (*Namgaladze et al*., 1998, 2013). The model covers the height range from 90 km to the geocentric distance of 15 Earth radii, takes into account the offset between the geomagnetic and geographic axes and calculates the three-dimensional variations of the main gas components' (O, O_2, N_2, NO, O_2^+, N_2^+, NO^+, O^+, H^+ and electrons) concentrations; neutral, ion and electron gases' velocities and temperatures by the numerical integration of the continuity, momentum and heat balance equations jointly with the equation for the electric potential. The latter equation takes into account the electric fields of the magnetospheric, dynamo and seismogenic origin:

$$\nabla[\sigma^T (\nabla\varphi - [\boldsymbol{v} \times \boldsymbol{B}]) - \boldsymbol{j}_m - \boldsymbol{j}_s] = 0, \qquad (1)$$

where σ^T is the ionosphere conductivity tensor, φ is the potential of the electrostatic field, $\boldsymbol{v}$ is the velocity vector of the neutral gas motion, $\boldsymbol{B}$ is the magnetic induction vector, $\boldsymbol{j}_m$ and $\boldsymbol{j}_s$ are the densities of the magnetosphere and seismogenic electric currents, respectively.

The UAM calculates the spatio-temporal variations of the near-Earth environment parameters in dependence on the inner state and outer forcing, which is controlled by input parameters, including the solar and geomagnetic activity indexes; the solar UV and EUV spectra; precipitating particles fluxes; field-aligned electric currents connecting the ionosphere with the magnetosphere and/or electric potential distribution at the polar cap boundaries. The substorm auroral currents are reflected by the auroral magnetic activity indexes AL, AU and AE. The geomagnetic activity indexes Dst and Kp characterize the geomagnetic storms. The UAM takes into account AL, AU, AE, Kp and Dst indexes to simulate the upper atmosphere behavior during geomagnetic storms and substorms. In this study we used the spatial distribution of the field-aligned currents' dependencies on AE and Kp and the spatial distributions of the precipitating electron fluxes depending on Kp according to the empirical model of the precipitations by *Hardy et al*. (1985).

To simulate the seismogenic effects, the vertical electric currents $\boldsymbol{j}_s$ = 20 nA/m^2 were added to Eq. (1) locally, above the earthquake epicenter. The chain of the electric current sources was setup at 3 nodes of the numerical grid along the tectonic fault (parallel to 30° geomagnetic meridian) with 15º longitude step between each node. This configuration is very similar to the configuration that was used in our previous simulations, where the middle-latitude earthquakes during quiet geomagnetic conditions have been studied (*Karpov et al.*, 2013; *Namgaladze et al.*, 2013). The numerical calculations have been carried out taking into account seismogenic currents and without them to distinct the effects of the seismogenic electric currents from the effects of magnetic activity, but not related with the earthquake preparation.

Results and discussion

The maximum of the geomagnetic storm main phase was at 00:00 UT on January 1, 2016. Fig. 1 shows the TEC disturbances after the main phase, which pronounce themselves, both in the GPS observations and UAM calculation results, in the form of the negative ionospheric phase (the TEC decrease relative to the background, quiet values) in the Southern (summer) hemisphere due to the thermosphere motion from the high latitudes toward the equator. The resulting effect is the decrease of the concentrations ratio between atomic and molecular components of the neutral gas (O/N_2 ratio) which leads to the increase of the ions recombination rates and, eventually, to the decrease of the electron density and TEC. The negative phase propagates from the high latitudes to, at least, the epicenter latitude, and *dTEC* reaches –50% according to the observations.

The addition of the seismogenic electric currents flowing upward (charging the ionosphere) drastically changed the calculated TEC pattern. The additional negative TEC disturbances appear in the area between the latitudes of the epicenter and magnetically conjugated point, ±30º to the East and to the West from the epicenter meridian (Fig. 1c). The GIM-TEC also shows the similar pattern in the same area (see Fig. 1a).

In the previous calculations performed by *Namgaladze et al.* (2013) and *Karpov et al.* (2013), where the middle-latitude earthquakes have been simulated, the main cause of the TEC disturbances was attributed to the electromagnetic plasma drift under the action of the electrostatic electric field generated as a result of the seismogenic vertical electric current (*Namgaladze et al.*, 2009). In the present case study, we consider the low-latitude earthquake, and here we deal mainly with the dynamo electric field of the induction origin, dominating at the low latitudes in comparison to the middle latitudes. It is added to the electrostatic field, and they both create the new electric potential and corresponding [$\boldsymbol{E} \times \boldsymbol{B}$] drift velocity patterns.

The UAM calculated zonal drift velocity patterns at 300 km are presented in Fig. 2. In the end result, the vertical electric currents lead to the generation of the electric field by the dynamo action, including the disturbance of the vertical component of the electric field and corresponding zonal drift at the latitudes between the epicenter and conjugated point. For the UAM calculations with the seismogenic vertical electric currents switched on (Fig. 2b), the resulting westward drift velocity is 3–4 times higher in comparison to the background values calculated without the seismogenic currents (Fig. 2a). According to the simulations results for this particular case study, an additional zonal drift is also higher than the vertical drift under the action of the zonal electric field, thus, it brings a greater effect to the resulting TEC disturbances.

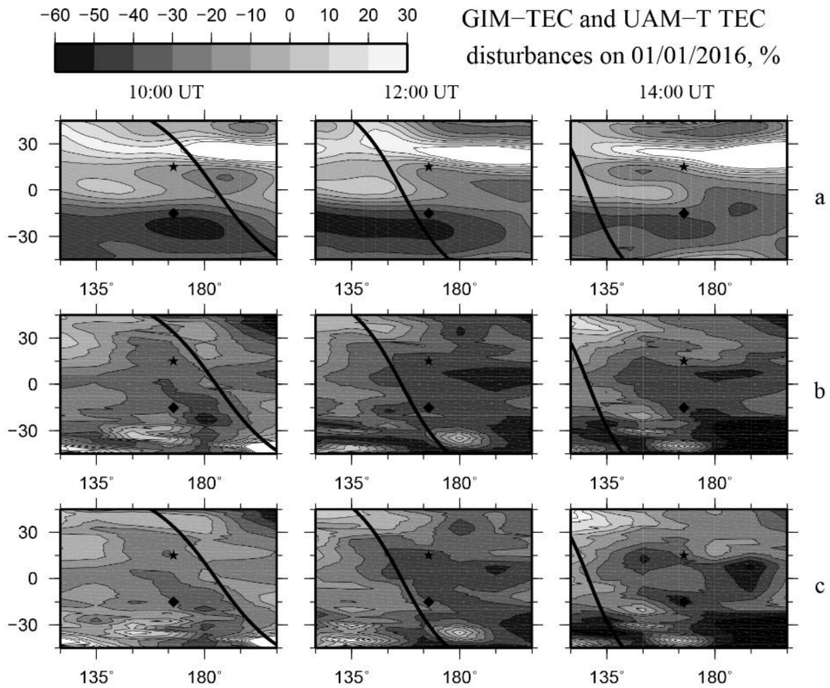

Figure 1. GPS observed and UAM-T calculated TEC disturbances (%) relative to the background values in the geomagnetic coordinates at 10:00 (*left panels*), 12:00 (*center*) and 14:00 UT (*right*) on January 1, 2016: **a**) GIM-TEC, **b**) UAM calculated without currents, **c**) UAM calculated with j_s = 20 nA/m^2. Black line denotes the terminator, black star and diamond represent the earthquake epicenter and magnetically conjugated point, respectively.

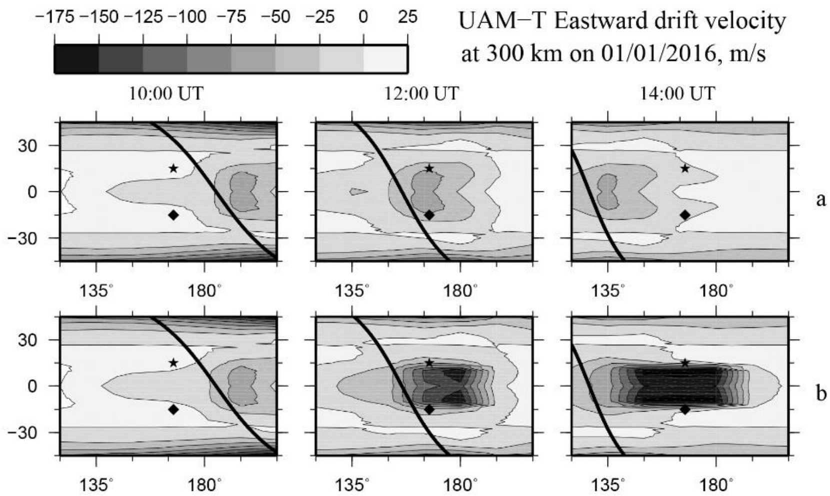

Figure 2. The UAM calculated eastward drift velocity (m/s) distributions at 300 km: **a**) without seismogenic currents; **b**) j_s = 20 nA/m^2.

Thus, the TEC disturbances caused by the upward seismogenic currents have a negative sign. Similar regions are clear visible in the GPS data. The presence of seismogenic currents leads to the increase of the upward electric field and corresponding westward electromagnetic drift of the ionospheric F2-layer plasma. This drift forms the negative TEC disturbances by transporting the plasma from the east to the west through the epicenter meridian, as it is seen in the observations and simulations results.

Finally, we should mention, that according to the GPS data, the strong TEC disturbances are clearly visible in the area North-East of the epicenter (Fig. 1a). At the first glance, they are similar to the ionospheric precursors of earthquakes, but their morphology is not consistent with the previously reported features of the pre-seismic TEC disturbances (*Namgaladze et al.*, 2013 and references in it). Firstly, there are no effects near the magnetically conjugated point in the Southern hemisphere. Secondly, these regions appeared in the GIM-TEC for the first time at

06:00 UT, i.e. earlier this day, at daytime. Thirdly, they are quite far from the epicenter. A comparison between the UAM calculations results with the seismic origin electric currents switched on (Fig. 1c) and off (Fig. 1b) shows that these positive GIM-TEC disturbances are not associated with seismogenic currents. We suppose that these disturbances are related with the high geomagnetic activity. In this period the ring current heats the outer part of the Earth's plasmasphere. It results in the increase the downward diffusion plasma flows from the plasmasphere to the ionosphere. These fluxes create the positive GIM-TEC disturbances regions at the Northern hemisphere due to the larger O/N_2 ratio at the ionospheric F2-layer altitudes in winter in comparison with the summer hemisphere.

Conclusions

The study presents the numerical calculations results of the ionosphere effects created by the vertical electric currents of the seismic origin. Simulations using the 3D global first-principle Upper Atmosphere Model (UAM) are compared with the GIM-TEC data for the high geomagnetic activity period preceding the M6.7 earthquake in India on January 3, 2016. The simulations have reproduced the general behavior of the ionosphere after the main phase of the geomagnetic storm on January 1, 2016 in the form of the negative TEC disturbances propagating from the high latitudes, especially strong in the Southern (summer condition) hemisphere. It was shown that the seismogenic currents' effects (ionospheric precursors of earthquake) can be revealed on the background of the global geomagnetic disturbances. They are visible as the regions with the additional negative TEC disturbances formed on the Eastern side of the epicenter meridian and extending to the Western side, both in simulations and observations. It was found that the vertical electric field which is the sum of the electrostatic and dynamo origin plays a decisive role in the formation of the ionospheric precursors of earthquakes at the low latitudes. They are related with the upward electric field and corresponding westward component of the electromagnetic [$\boldsymbol{E}$ x $\boldsymbol{B}$] drift.

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