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EARTHQUAKES' INFLUENCE ON THE SPACE WEATHER

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Abstract. The Total Electron Content anomalies observed before strong earthquakes have been considered as possible ionospheric earthquakes precursors. Their possible physical mechanism related with seismogenic electric field has been supposed and the results of the numerical modeling of the ionospheric effects of the seismogenic electric field have been discussed.

Introduction

Nowadays GNSS-based (Global Navigation Satellite Systems) techniques are widely used to investigate the ionosphere TEC (Total Electron Content) modifications and in particular the ionospheric effects associated with seismic events. The dense network of GNSS and GPS (Global Positioning System) receivers fulfills simultaneous coverage in global scale and allows to plot and analyze the global maps of the TEC. The TEC is the integral amount of electrons in the vertical column with 1 m^2 cross-section over the given point. The main contribution in the TEC is produced by the ionospheric F2-layer electron density (heights 200-1000 km), i.e. by the region of the maximal ionospheric electron density. The time variations of TEC and NmF2 are very similar. Therefore, we can consider both TEC and NmF2 variations as equally important space weather characteristics.

Morphology of the TEC anomalies observed before strong earthquakes

The extensive studies of the ionospheric earthquake precursors in the GPS TEC measurements [e.g. Liu et al., 2004, 2006; Pulinets et al., 2003; Pulinets and Boyarchuk, 2004; Pulinets and Ouzhounov, 2010; Zakharenkova et al. 2007a,b; 2008] revealed that for strong mid-latitudinal earthquakes the seismo-ionospheric anomalies very often look like:

(1) local long-living TEC increases or depressions that are situated in the vicinity of the earthquake epicenter area. The amplitude of plasma modification reaches the values of 30-90% relative to the non-disturbed level. Positive modifications of the TEC usually dominate.

(2) The vertical projection of the epicenter position does not mandatory coincide with the maximum phenomenon's manifestation location.

(3) The zone of the anomaly maximum manifestation extends larger than 1500 km in latitude and 3500-4000 km in longitude. The shapes and dimensions of the disturbed areas are kept rather stable.

(4) The size of the area depends on the earthquake's magnitude.

(5) Similar effects are often reported at the magnetically conjugated area.

(6) The anomalies are reported from several days or hours to couple weeks before the earthquake release moment.

(7) In case of the strong low-latitudinal earthquakes there are effects related to the modification of the ionospheric F2-region equatorial anomaly: increase or decrease of the equatorial anomaly with trough deepening or filling.

This traditional pre-earthquake TEC modification scheme, reported by many authors, should be extended with the following two new signatures revealed in some recent investigations of the last strong earthquakes:

(8) "Ban-time" effect at the near-noon hours [Namgaladze et al., 2011], i.e. the TEC anomaly reduction with subsolar point income takes place, and

(7) sun-rise terminator income should trigger anomaly depletion while sun-set terminator income trigger the anomaly recovery. It should be noticed that many ULF precursors also dominate at night-time (see, e.g. [Hobara et al., 2004]).

Physical interpretation of the TEC anomalies observed before strong earthquakes

We consider that the most probable reason of the NmF2 and TEC disturbances observed before the earthquakes is the vertical drift of the F2-region ionospheric plasma under the influence of the zonal electric field of seismogenic origin. Due to the high electrical conductivity of the geomagnetic field lines they can be assumed to be electrical equipotentials, so that electric fields along these lines are zero or very small. Electric fields at heights > 170 km are therefore practically always perpendicular to the geomagnetic field lines. These mutually perpendicular electric (**E**) and magnetic (**B**) fields force the ionospheric plasma to move with the so called E×B plasma drift velocity (equal to $\mathbf{E}\times\mathbf{B}/B^2$), i.e. in the direction perpendicular to both. In this drift motion, ions and electrons move together with the same velocity, i.e. there is no charge separation and they do not create electric currents.

In the middle latitudes the upward electromagnetic 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 and, consequently, with lower loss rate of dominating ions O+ in the ion-molecular reactions. The electric field of the opposite direction (westward) creates the opposite – negative – effect in NmF2 and TEC. In the low latitude regions (near the geomagnetic equator) the increase of the eastward electric field leads to the deepening of the equatorial anomaly minimum ("trough" over the magnetic equator in the latitudinal distribution of electron concentration) due to the intensification of the fountain-effect [Brunelli and Namgaladze, 1988].

The TEC is formed mainly by the F2-layer plasma density. NmF2 and TEC disturbances related with magnetic activity are created by the neutral atmosphere (neutral gas composition, internal gravity waves and winds) and electric field variations. But it is impossible to localize neutral atmosphere disturbances at a limited area, they will propagate away from the source. Therefore, there are strong arguments in favor of the idea of an electric field of seismic origin as the main cause for the TEC anomalies observed before earthquakes: (a) the geomagnetically conjugate ionospheric precursors [Pulinets et al., 2003]; (b) effects related to the ionospheric F2-region equatorial (Appleton) anomaly controlled by the zonal electric field [Depueva and Ruzhin, 1995; Pulinets and Legen'ka, 2002]; (c) "ban-time" at the near-noon hours [Namgaladze et al., 2011a].

Many authors [e.g., Pulinets and Boyarchuk, 2004; Pulinets and Ouzhounov, 2010; Chmyrev and Sorokin, 1999; Sorokin et al., 2005a,b; 2006, 2007] strongly rely on the hypothesis of a seismogenic electric field related to the vertical turbulent transportation of injected aerosols and radioactive particles (radon isotopes). The increase of the atmospheric radioactivity level during the earthquake formation leads to the enlargement of the ionization and electric conductivity of the near-ground atmosphere. The joint action of these processes leads to an intensification of an electric field in the ionosphere up to the value of units-tens mV/m [Chmyrev et al., 1989]. Ionosphere response on such electric fields were investigated mainly using 1D models and for the lower ionosphere [Hegai et al.,1997; Kim et al., 2002].

Freund [2011] proposed another mechanism of the near-ground atmosphere layer ionization basing on the so called "positive holes": most crustal rocks contain dormant electronic charge carriers in the form of peroxy defects; when rocks are stressed, peroxy links break, releasing electronic charge carriers, known as positive holes. The positive holes are highly mobile and can flow out of the stressed subvolume. F. Freund expects this mechanism to be significantly more efficient than the above-named radon-related ones.

Modeling of the TEC anomalies observed before strong earthquakes

We have calculated the ionospheric electric field related with external electric current variations in the lower atmosphere. This current is assumed to be formed due to the convective upward transport of charged aerosols and their gravitational sedimentation in the lower atmosphere and is related with the occurrence of ionization source due to seismic-related emanation of radon and other radioactive elements into the lower atmosphere over the earthquake preparation area [Chmyrev and Sorokin, 1999; Sorokin et al., 2005a,b; 2006, 2007; Pulinets and Boyarchuk, 2004; Pulinets and Ouzhounov, 2010; Pulinets and Tsybulya, 2010] or with the so-called "positive hole" electric field ionization [Freund, 2011].

We used this vertical current as the model input for the calculations of the ionospheric electric field and corresponding TEC variations using the UAM – Upper Atmosphere Model [Namgaladze et al., 1988, 1990, 1998]. The Upper Atmosphere Model is a global, three-dimensional, time-dependent, numerical model simulating the thermosphere, ionosphere, plasmasphere and inner magnetosphere of the Earth as a single system. It was initially developed at the Kaliningrad observatory (now West Department) of IZMIRAN [Namgaladze et al., 1988, 1991] and then extended at the Polar Geophysical Institute of the Russian Academy of Sciences and at the Murmansk State Technical University [Namgaladze et al., 1998a,b]. The model includes the equations of the continuity, momentum and heat balance for neutral and charged particles and the electric potential equation and calculates the concentrations, velocity vectors and temperatures of basic neutral (O_2, N_2, O) and charged (NO^+, O_2^+, O^+, H^+ and e) components of the atmosphere at the altitude range from 60 km to $15R_e$.

To estimate the upper limit for the magnitudes of the vertical electric current applied, we looked through the publications available. Sorokin et al. [2005a,b; 2006, 2007] calculated the ionospheric electric field related to external electric current variations in the lower atmosphere. According to Sorokin et al., an external current density of about 10^{-6} A/m^2 within an area of about 200 km in radius (approximately 130 000 km^2) is required to create an electric field of several mV/m in the ionosphere.

To build model difference maps (of the electric potential, zonal and meridional electric field and TEC) we firstly performed a regular calculation without any additional electric current sources (set as lower boundary condition) to use the results as quiet background values. Then an external electric current flowing between the lower atmosphere and the ionosphere over the Haiti earthquake (Jan. 12, 2010, 21:53 UT, M 7.0) epicenter area has been used as model input for the calculations of the ionospheric electric field and the corresponding TEC variations. Several spatial configurations and magnitudes of these currents have been taken into consideration: (1) "point" current (equivalent to one cell) sources of different signs and magnitudes, given in a single node of the numerical grid and (2) "line" sources.

According to UAM simulations point current sources with magnitudes of about 10^{-5} A/m^2 and 10^{-6} A/m^2 given in a single grid node (corresponding to one grid cell of 5º × 2º or approximately 500 km × 200 km, and averaged vertical electric current densities of 5×10^{-6} A/m^2 and 5×10^{-7} A/m^2, respectively) induced extremely strong and unrealistic TEC disturbances and very intense vertical drift motions. Point sources of 10^{-9} A/m^2 and 5×10^{-9} A/m^2 triggered TEC disturbances not exceeding 15-30% in magnitude.

The "line" kind sources have been simulated as vertical external currents with a magnitude of 4×10^{-8} A/m^2 directed from the ionosphere to the Earth set centric at 9 numerical grid nodes with 5º longitudinal steps along the magnetic parallel of the earthquake epicenter. It corresponds to an external electric current density of 2×10^{-8} A/m^2 set on the region of approximately ~200 km × ~4000 km (2º along the meridian and 40º along the parallel). The generated TEC disturbances have reached ~20-50% by magnitude depending on the current's spatial distribution and lifetime. Simulation results are presented in the paper by Namgaladze et. al. [2011b] in this issue.

As one can see, the additional electric potential generated by the external current reduces down to zero when approaching the terminator in both (modelled and observed) cases. The corresponding TEC disturbances disappear later than the electric potential with a time-lag of about 4-6 hours. The simulations underestimate the observed magnitude of anomalous TEC increase at the northern and overestimate it at the southern hemisphere. Both (modelled and observed) cases show stronger TEC magnitudes at the magnetically conjugated region in comparison with the near-earthquake epicenter area.

Discussion and conclusions

Summarizing the numerical simulation results with external electric currents flowing between the lower atmosphere and ionosphere due to seismo-induced conductivity changes of the underlying atmosphere column, one can state that they reproduce the main features of the TEC variations. In both the GPS observations and model cases we have: (1) areas of the increased TEC existed and are localized in the near-epicenter area. (2) Magnetic conjugation took place. (3) TEC disturbances at the magnetically conjugated area were stronger by magnitude than in the near-epicenter region. (4) The amplitude of TEC enhancements reached 50% and more. (5) Negative structures (areas of the TEC reduction) existed westwards and equatorwards relative to the positive ones. (6) Approaching the sunrise terminator with the well-conducting sunlit ionosphere triggered a shift of the anomaly to the night-side and causes the subsequent suppression of the TEC variations both at the epicenter and in the magnetically conjugated regions. (7) The anomalies did not exist during the near-noon hours. Such behavior and the lifetime agreed with [Akhoondzadeh and Saradjian, 2011] results. The obtained morphological features also agreed with [Pulinets and Tsybulya, 2010].

We should notice that a few discrepancies between the observations and the model results persist: (1) the simulations underestimate the amplitudes of the TEC anomaly at the northern hemisphere and overestimate them at the southern one in comparison with the observations. (2) Negative structures are stronger than the observed ones by magnitude in the model case. (3) The increased TEC area occupies a smaller region in the model case. (4) The isoline patterns and the magnitudes differ from the observed ones but not drastically. The discrepancies between the simulation results and the GPS observations could be due to the rather simplified assumptions about the external electric field sources, their density distribution and acting regime.

Night domination effects, the existence of a "ban-time" and the terminator-driven TEC anomaly suppression should be due to the changes of the conductivity of the ionosphere. It is related to the crossing of the sunrise terminator, where the well-conducting sunlit ionosphere leads to a depression of the electric potential disturbances and to a reduction of the electric field, generated by the externally driven electric current.

The obtained vertical currents required for creating TEC anomalies of about 50% (2 10^{-8} A/m^2) are very large, they exceed the so called "fair weather" currents in 10^4 times. Perhaps, such currents are the upper limit of the possible vertical currents between the Earth and ionosphere. They can exist only limited time at the limited areas during preparation of the very strong earthquakes such as in Haiti 2010 and Japan 2011 cases. It is very difficult to observe them directly due to lack of the appropriate instrumentation net. But their ionospheric effects can be revealed by the TEC monitoring at least in cases of very strong earthquakes.

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