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Aerosols and seismo-ionosphere coupling: A review

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ABSTRACT

The role of atmosphere aerosols in the global electric circuit, particularly during earthquakes preparation periods, is discussed in this review paper. Aerosols participate in production and transport of electric charges as well as in clouds formation. Satellite imagery shows increased aerosol optical depth over the tectonic faults and formation of the anomalous clouds aligned with the faults shortly before the earthquake shocks. At the same time variations of the ionospheric electric field and total electron content (TEC) are observed. We assume that the vertical electric current is generated over the fault due to the separation and vertical transport of charges with different masses and polarities. This charges the ionosphere positively relative to the Earth in the same way as the thunderstorm currents do. The resulting electric field in the ionosphere drives F2-layer plasma via the electromagnetic $[\vec{E} \times \vec{B}]$ drift and decreases or increases electron density depending on the configuration of the electric field, thus, creating observed negative or positive TEC disturbances. The important role of the electric dynamo effect in these processes is underlined.

1. Introduction

The lithosphere-atmosphere-ionosphere coupling (LAIC) is a hot topic in the field of the solar-terrestrial physics, both for the experimental and theoretical studies. Variations of atmosphere and ionosphere parameters observed several days before the strong earthquakes are of the greatest interest (Pulinets and Boyarchuk, 2004; Liperovsky et al., 2008; Harrison et al., 2010; Hayakawa and Hobara, 2010; Kachakhidze et al., 2014; Pulinets et al., 2015; Sorokin and Ruzhin, 2015). Below we try to unite the results of the ionosphere and atmosphere observations (including electric fields, total electron content disturbances, atmosphere aerosols and atmosphere behavior over the tectonic faults), physical interpretations and numerical simulations for the explanation of the LAIC origins to develop the methods of earthquakes prediction in the future.

Among the many different types of the pre-seismic ionospheric variations, in this paper we highlight perturbations of the electric field observed by Intercosmos Bulgaria and DEMETER satellites (Chmyrev et al., 1989; Gousheva et al., 2009; Zhang et al., 2012) as well as the total electron content (TEC) variations derived from the GPS data (Liu et al., 2006; Zakharenkova et al., 2008; Namgaladze et al., 2013; Pulinets and Davidenko, 2014). Namgaladze et al. (2013) concluded that there exist a set of common features of the GPS TEC variations which can be considered as the ionosphere earthquake precursors. The abnormal TEC disturbances were described as the long-living and stable positive and/or negative perturbations reaching 30–90% and more in comparison to the background values; the manifestation zone extended to 1500–4000 km; and the lifetime exceeded 4–6 h. In addition to the epicenter region, the TEC disturbances were often detected in the opposite hemisphere, in the vicinity of the magnetically conjugated point. Anomalies are often reduced in daylight and restored at night.

Namgaladze et al. (2009a, 2009b) simulated the TEC response on disturbances of the ionospheric electric fields and have shown that the electromagnetic $[\vec{E} \times \vec{B}]$ drift of the ionosphere F2-layer plasma caused by the electric field of ~10 mV/m can be responsible for generation of TEC disturbances. The simulated TEC variations were similar to the observed ones, but the origin of an additional electric field in the ionosphere due to the seismic activity was not explained. Several studies by Namgaladze et al. (2009a, 2009b); Klimenko et al. (2011); Kuo et al. (2011, 2014); Karpov et al. (2013) modeled numerically the ionosphere TEC variations by using various sources related with the earthquakes preparations. The nature of these sources is the most important question in the LAIC problem, and several different physical mechanisms have been proposed.

Pulinets et al. (2015) considered the pre-seismic ionosphere effects as a results of intensification of natural radioactivity near the Earth surface. Radioactive gases such as radon, emanating from the Earth crust, lead to

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the increased ionization of the air boundary layer, changes of the air electrical conductivity and, eventually, to an electric field penetrating into the ionosphere. Indeed, the ground based observations show perturbations of the electric field in the surface layer from several V/m to 1 kV/m for the very short period of time, several days before earthquakes (Hao et al., 2000; Rulenko, 2000). However, calculations by (Denisenko et al., 2013; Xu et al., 2015) have shown that the electric field couldn't penetrate the low-conducting atmosphere and create noticeable changes in the ionosphere. According to the calculation results, the resulting electric field at the height of 90–100 km in this case is about several μV/m, i.e. it is at least three orders of magnitude less than the intensity of the quasi-static electric fields observed by Intercosmos Bulgaria 1300 and DEMETER over seismic regions. Thus, it is impossible to explain the occurrence of the seismogenic electric field in the ionosphere by its direct penetration from the ground through the almost non-conducting atmosphere.

Freund et al. (2009) proposed principally different mechanism of the seismogenic electricity generation. When rocks are stressed, the peroxy links break and release highly mobile charge carriers accumulating at the Earth surface. These carriers known as positive holes, lead to the massive ionization of the air near the ground and under certain conditions to the corona discharges. Freund claims that the process is more effective than the ionization by radon, and the corresponding electric currents on the orders of 10–100 nA/m^2 were detected in the laboratory experiments with pressed rocks.

Sorokin and Ruzhin (2015) have summarized their previous studies (e.g. Sorokin et al., 2007; Sorokin and Hayakawa, 2013) on the generation of the quasi-static electric fields in the ionosphere. Their concept is based on the generation of the additional electromotive force in the lower atmosphere due to the injection of the soil gases. Vertical transport of charged aerosols by the atmospheric convection and turbulent diffusion and the gravitational sedimentation of charged aerosols lead to the generation of the external electric current. According to estimations, its value reaches 10^{-8}–10^{-6} A/m^2, while the intensity of the electric field was estimated as ~10 mV/m in the ionosphere and ~100 V/m at the Earth surface. Sorokin and Ruzhin (2015) pointed to the similarity between the physical mechanisms of the ionosphere responses to the earthquake preparation processes and the large-scale meteorological events, such as typhoon formations and storm activity. Earlier, Harrison et al. (2014) have discussed possible relationships between earthquakes and clouds formed over the faults, as well as ion-aerosol-cloud interactions (Harrison and Carslaw, 2003).

We review the pre-seismic ionospheric and atmospheric observation results in detail in Section 2 of the paper, and summarize the numerical simulations of ionosphere effects in Section 3. Finally, in Section 4 we explain our thoughts on the nature of seismogenic electricity generation in the low atmosphere and its delivery to the ionosphere. We hope to show that origin of the electric fields observed over the tectonic faults is very similar (if not identical) to the process of the ionosphere charging by the thunderstorm generator, where aerosols play main role. The important electric dynamo effects are shown in the modeling results as well.

2. Observations

In the past decade a numerous ground based and satellite observations in the whole range of altitudes from the Earth surface up to the heights of the ionosphere were conducted aiming at detection of possible effects associated with seismic activity. Special attention was paid to the anomalous changes in the ionosphere several days and hours prior to large earthquakes in order to reveal specific features of anomalies explain their generation and develop methods of early detection. Various types of pre-seismic anomalies called the ionospheric precursors of the earthquakes are observed in the ionosphere. The ground and satellite sensing shows variations of the VLF/LF and ULF electromagnetic emissions (Kachakhidze et al., 2014); abnormal changes of amplitude and phase characteristics of VLF radio waves propagations (Rozhnoi et al., 2012); formation of sporadic layers at altitudes of the E-layer (90–150 km) and changes of critical frequencies of the E-layer (Silina et al., 2001; Liperovskaya et al., 2006a); changes of critical frequencies and maximum heights of the F2-layer; modifications of the equatorial ionization anomaly in the form of crests offset towards the equator or the poles and deepening or filling of the through between the crests (Depueva and Rotanova, 2001; Liperovskaya et al., 2006b) as well as disturbances of the electric and magnetic fields components (Chmyrev et al., 1989; Gousheva et al., 2009; Zhang et al., 2012) in the periods from a few days to a few hours before the shocks. It has been also reported about the changes of the electron and ion concentration, velocities of the vertical ion drift and the changes of ion and electron temperatures (Ryu et al., 2014). The seismo-ionospheric variations were observed in the periods with the quiet solar and geomagnetic activity.

2.1. Total electron content variations

Ground based and satellite observations of the ionosphere have considerable limitations. Sporadic measurements are conducted either locally, or along the path of the radiosounding, or along the orbit of the satellite, therefore, they do not provide the global and constant monitoring of the ionosphere parameters. A new era of the ionosphere state monitoring started with the development of the global satellite navigation systems, such as Global Positioning Systems (GPS) and GLONASS which combine a group of satellites and dense network of ground stations receiving signals from these satellites. By calculating the phase difference of signals between the satellites and ground stations, the integrated electron density in the vertical column of the ionosphere is estimated. It is known as the total electron content (TEC) and is measured in the TEC units (TECU), where $1TECU = 10^{16}$ $electrons/m^2$. The most popular product to analyze the ionosphere state is the global ionosphere maps (GIM) of the TEC provided by NASA (National Aeronautics and Space Administration) in the IONEX format (Schaer et al., 1998). The GIM-TEC covers ±87.5° of latitude and ±180° of longitude with the spatial resolution of 2.5° and 5.0°, respectively, and with cadence of 2 h.

The GIM-TEC of the ionosphere is the subject of many studies concerning variations of the ionosphere in the periods before significant earthquakes (Pulinets and Boyarchuk, 2004; Liu et al., 2006; Zakharenkova et al., 2008; Namgaladze et al., 2012, 2013; Pulinets and Davidenko, 2014; Zhu et al., 2016; Parrot et al., 2016). Based on the analysis of many case studies, the set of morphological features of the pre-seismic TEC variations have been identified as follows (Namgaladze et al., 2013). 1) The pre-seismic anomalies represent themselves as the positive and/or negative deviations (increases or decreases of the TEC) of ≥30–90% relative to the quiet values. 2) The spatial dimensions of the disturbed areas reach more than 1500 km in latitude and 3500 km in longitude. 3) Their formation occurs above the epicenter or near it from several days and hours to 1–2 weeks before the shock. 4) The lifetime of the seismic disturbance reaches 12 h in cases of significant earthquakes. 5) In contrast to the disturbances associated with geomagnetic and solar activity, the pre-seismic perturbations remain practically stable and motionless and do not change their own shape. 6) With the sunrise approach there is a significant reduction of disturbances, often until their complete disappearance followed by recovery at night. 7) The same effects are often observed in the magnetically conjugated region. 8) In case of the strong low-latitude earthquakes there are effects related to the modification of the equatorial ionization anomaly. 9) Similar effects in the TEC are also observed during volcanic activity and dust storms (Pulinets and Davidenko, 2014) as well as tropical cyclones (Guha et al., 2016).

2.2. Ionospheric electric field variations

For the first time perturbations of the quasi-stationary electric fields of the ionosphere associated with the preparatory processes of earthquakes have been identified by Chmyrev et al. (1989). In a 15min