Modern Applied Science; Vol. 7, No. 6; 2013
ISSN 1913-1844 E-ISSN 1913-1852
Published by Canadian Center of Science and Education

Generation of Seismic-Related DC Electric Fields and Lithosphere-Atmosphere-Ionosphere Coupling

Valery Sorokin[1] & Masashi Hayakawa[2]

[1] Pushkov Institute of Terrestrial Magnetism, Ionosphere and Radio Wave Propagation (IZMIRAN), Russian Academy of Sciences, Troitsk, Moscow, Russia

[2] The University of Electro-Communications (UEC), Advanced Wireless Communications Research Center (AWCC), 1-5-1 Chofugaoka, Chofu Tokyo, Japan

Correspondence: Masashi Hayakawa, The University of Electro-Communications (UEC), Advanced Wireless Communications Research Center (AWCC), 1-5-1 Chofugaoka, Chofu Tokyo 182-8585, Japan. Tel: 81-424-44-6349. E-mail: hayakawa@hi-seismo-em.jp

Received: March 7, 2013 Accepted: April 5, 2013 Online Published: May 6, 2013

doi:10.5539/mas.v7n6p1 URL: http://dx.doi.org/10.5539/mas.v7n6p1

Abstract

This paper reviews modeling of the influence of earthquake (EQ) preparation processes on the ionosphere through the electric field and electric current occurring in the global atmosphere–ionosphere electric circuit. Our consideration is based on the satellite-and ground-based experimental data of electric fields, plasma and electromagnetic perturbations obtained for several days before an EQ. We have ruled out the models which are not consistent with the experimental data on the electric fields in the ionosphere and also on the ground surface. There has then been proposed a new model of the generation of electric field on the basis of injection of charged aerosols into the atmosphere, and we discuss the mechanism of lithosphere-atmosphere-ionosphere coupling. It is then shown that such changes in the electric field within the ionosphere induce a variety of plasma and electromagnetic phenomena associated with an impending EQ.

Keywords: earthquakes, earthquake precursors, DC electric field, lithosphere-atmosphere-ionosphere coupling

1. Introduction

Numerous plasma and electromagnetic anomalies observed within the ionosphere above the regions of seismic activity are found as evidence that processes of earthquake (EQ) preparation effects take place in the ionosphere for several days before an EQ. Observations of anomalous plasma and electromagnetic phenomena in the ionosphere over the zones of seismic activity were extensively discussed in many reviews and books (Gokhberg et al., 1988; Liperovsky et al., 1992; Molchanov, 1993; Buchachenko et al., 1996; Varotsos, 2001; Hayakawa & Molchanov, 2002; Pulinets & Boyarchuk, 2004; Tronin, 2006; Sorokin, 2007; Molchanov & Hayakawa, 2008; Hayakawa, 2009, 2012; Uyeda et al., 2009; Sorokin & Chmyrev, 2010; Hayakawa & Hobara, 2010), and these phenomena are considered as manifestation for the existence of lithosphere-atmosphere-ionosphere (LAI) coupling or interaction. There are ionospheric effects as a result of the simultaneous actions of various factors such as acoustic waves, electric fields, electromagnetic radiation, chemically active substances, etc. An important role in the formation of these factors is played by aerosols of the lower atmosphere, which influence its conductivity and forms an external electric charge and a current by atmosphere dynamics. Seismic activity is accompanied by the injection of soil aerosols and radioactive substances into the atmosphere, so that the enhancement of such activity in seismic regions changes the state of ionospheric plasma and electromagnetic field at the temporal scale for a few days before an EQ.

An analysis of satellite data showed the presence of electromagnetic perturbations over a wide frequency range. These perturbations are localized within the magnetic field tube conjugate with the seismic focus of an impending EQ. There are quite many papers on those satellite recordings of wave and plasma disturbances possibly associated with an individual EQ or several strong EQs (Parrot & Lefeuvre, 1985; Larkina et al., 1989; Chmyrev et al., 1989; Galperin et al., 1993; Molchanov et al., 1993; Pulinets et al., 1994; Parrot, 1994, 2009, 2011; Chmyrev et al., 1997). The presence of electron density fluctuations in the ionosphere above seismic regions was substantiated by ample satellite data (Afonin et al., 1999), and there were recorded changes in the ionic composition and temperature of the plasma in the upper ionosphere and perturbations of the height profile of the ionospheric F region (Pulinets et al., 1994; Boskova et al., 1994). An analysis of satellite images of the Earth's surface in the infrared (IR) frequency range showed the presence of stable and unstable components of the anomalous IR radiation flux above active crust faults; this flux corresponded to an increase in the temperature of the near-Earth layer by several degrees (Qiang et al., 1999; Tronin, 1999; Tronin et al., 2002; Ouzounov et al., 2012). Simultaneously with electromagnetic and plasma phenomena in the ionosphere, there were observed an increase in the concentration of certain gases (e.g., H_2, CO_2, and CH_4) by several orders of magnitude, an increase in atmospheric radioactivity (related to such radioactive elements as radon, radium, uranium, thorium, and actinium and their decay products), and an increase in the injection of soil aerosols (Alekseev & Alekseeva, 1992; Virk & Singh, 1994; Heincke et al., 1995; Igarashi et al., 1995; Biagi, 2009; Yasuoka et al., 2012).

The ground-based observations which are aimed at searching electromagnetic phenomena related with processes of EQ preparation and evolution, have started in the last tens of years of XX century. The following phenomena were observed with a lot of hopes: ULF magnetic and electric emissions (Fraser-Smith et al., 1990; Molchanov et al., 1992; Kopytenko et al., 1993; Hayakawa et al., 1996a), acoustic emissions (Gorbatikov et al., 2002), amplitude and phase anomalies of subionospheric VLF/LF signals from powerful transmitters (Hayakawa et al., 1996b; Molchanov & Hayakawa, 1998; Rozhnoi et al., 2004), ionosphere perturbations measured by the ionospheric sounding (Pulinets et al., 1994; Liu, 2009), airglow anomalies (Gladychev & Fishkova, 1994) and some others. Uniform and global-size observations of possible ionospheric effects from many EQs can be carried out together with the estimation of the size of seismo-active region.

A joint analysis of observational results led us to conclude that seismic activity stimulated the development of intense processes in the lower atmosphere. Earth's surface seismic waves, chemically active and radioactive substances, and charged aerosols are likely to act simultaneously on the lower atmosphere. There then occur heating of the lower atmosphere, sharp changes in its electrophysical parameters, the generation of acoustic waves, and the formation of external electric currents. The acoustic action also appears on the ionosphere because of the upward propagation of infrasonic waves (Liperovsky et al., 1997). Processes in the lower atmosphere (seismic waves, atmosphere heating, and the injection of gases) result in the generation and upward propagation of internal gravity waves (IGWs), which might perturb the ionosphere (Gokhberg et al., 1996). The formation of ultralow-frequency radiation on the Earth's surface by lithospheric sources is considered in Molchanov and Hayakawa (1995), Molchanov (1999), Surkov and Pilipenko (1999), and Sorokin and Pokhotelov (2010), and the possibility of its penetration into the ionosphere is discussed in Molchanov et al. (1995). Numerous studies of the nature of atmosphere-ionosphere interactions aimed at determining their mechanism were performed. For instance, the physical processes of formation of currents in the lithosphere and propagation of their radiation into the ionosphere were considered in Fitterman (1979) and Pilipenko et al. (1999). Alperovich et al. (1979) discussed acoustic actions resulting in ionospheric perturbations and the generation of geomagnetic pulsations was discussed. Similar works were performed for numerous chains of processes between sources and measured parameters. Another approach to study EQ precursors consists in a joint analysis of a set of possible parameters observed. Such an analysis can be physically based on a model that makes it possible to interpret satisfactorily most of satellite- and ground-based observations as a manifestation of one cause. In this case measured parameters proved to be interrelated by certain regularities. One of the important problems of atmosphere-ionosphere interactions is the search for a chain of processes related to acting factors and identification of a set of observed effects of a common nature. It is considered that principal causes of lithosphere–ionosphere coupling are the generation of both acoustic waves and electric field in the seismic region. Below we discuss only one of these influence factors; namely, the purpose of this paper is to discuss the cause and consequences of electric field occurring at an eve of EQs.

2. Basic Properties of DC Electric Fields

The seismic-related DC electric fields in the ionosphere had been, for the first time, revealed by Chmyrev et al. (1989). They analyzed the vertical component of quasi-static (DC) electric field E_z, and we show one example. They observed such an enhanced E_z onboard the "Intercosmos-Bulgaria 1300" satellite within a 15-min interval before an EQ occurred on January 12, 1982 at 17.50.26 UT. The quasi-static electric field with amplitude of 7-8 mV/m was observed in two zones: above the EQ focus and in its magnetically conjugate region, and the size of those zones was 1°~1.5° in latitude.

Subsequent investigations of DC electric field in the ionosphere based on direct satellite measurements over seismic regions were carried out by Gousheva et al. (2006, 2008, 2009), who analyzed hundreds of seismic events in order to detect DC electric field enhancement in the ionosphere connected with EQs. Seismic events with different magnitudes in different tectonic structures at different latitudes were observed. They selected the orbits with distance less than 250 km with respect to the EQ epicenter, not crossing terminator and during low magnetic activity. Let us present one case study of their registration results. The DC electric field 5-10 mV/m was detected in the magnetic conjugate regions 11–13 hours before two EQs (magntitude around 5) occurring on 25.08.1981 at 16:54:39 UT and 17:29:07 UT correspondingly (Gousheva et al., 2008). Statistical analyses of the satellite data by Gousheva et al. (2008, 2009) led them to make a conclusion on the existence of seismic-related quasi-static electric field in the ionosphere. The duration of electric field disturbances with amplitude of the order of 10 mV/m can be up to 15 days, and the electric field disturbances in the daytime and nighttime ionospheres were on the same order.

Direct observations of quasi-static electric field in the ionosphere are confirmed by computational modeling of the ionospheric perturbation occurring at an eve of EQs. Spatial distributions of the total electron content (TEC) obtained by GPS receivers in the seismic region were analyzed (Liu, 2009; Pulinets, 2009a), and those TEC anomalies are tried to be interpreted with the use of global model of the upper atmosphere which describes the thermosphere, ionosphere and plasmasphere as an integrated system. The model is based on integration of the non-stationary three-dimensional equations of continuity, impulse and energy balance of multi-component gas simultaneously with the equation for electric field potential. In the frame of computer simulations there was sought an additional electric field which leads to the TEC perturbation coincident with the one observed in the EQ preparation region. For example, Zolotov et al. (2008) considered an EQ in Peru on 26.09.2005. The characteristics of TEC disturbances were given in Zakharenkova et al. (2008), and the TEC perturbation was observed during six days before the EQ from 21.09.2005 till 26.09.2005. Based on the computer simulations Zolotov et al. (2008) have shown that the observable TEC perturbation is due to an additional electric field with an amplitude of 6 mV/m. It is further suggested by Klimenko et al. (2011, 2012) and Namgaladze et al. (2009) that a possible general cause of TEC perturbation is a vertical plasma drift by the zonal electric field. Computer simulations by Klimenko et al. (2012) have shown that the amplitude of electric field disturbance is required to be 3-9 mV/m.

At the same time, observations of the quasi-static electric field on the Earth's surface in seismic regions were carried out by different workers (Kondo, 1968; Jianguo, 1989; Nikiforova & Michnovski, 1995; Vershinin et al., 1999; Hao et al., 2000; Rulenko, 2000). Analyses of those publications show that the local electric field surges with large amplitude reaching several kV/m are observed during the EQ preparation, but their duration is of the order of ten minutes. However, there are absent visible electric field disturbances with duration of several days observed simultaneously over the horizontal distance of hundreds of kilometers.

The indirect confirmation of electric fields occurring in the atmosphere is the observational results of VHF emissions propagating from the source located in the troposphere over a region of EQ preparation (Vallianatos & Nomicos, 1998; Ruzhin et al., 2000; Hayakawa et al., 2006; Ruzhin & Nomicos, 2007; Yonaiguchi et al., 2007a, b; Yasuda et al., 2009). VHF radiations are found to have occurred for several days before an EQ, and their duration reaches several days. If the VHF electromagnetic radiation propagated over a distance more than a wavelength, then the condition of optical propagation is fulfilled, so that it is possible to receive the signal at distance of the order of 300 km just in the case that its source is located in the atmosphere above Earth's surface. The region of generation of VHF electromagnetic radiation is found to be at the altitudes of the order of several kilometers above EQ epicenters located behind the horizon (Fukumoto et al., 2001; Yasuda et al., 2009).

Consequently, both the direct and indirect data of DC electric field observations in the atmosphere and ionosphere over a seismic region allow us to formulate its basic properties. The basic experimental results are summarized as follows:

- The enhancement of seismic activity produces DC electric field disturbances in the ionosphere of the order of 10 mV/m.
- These disturbances occupy the region with horizontal spatial scale from hundreds to thousands km over the seismic region.
- DC electric field enhancements occur in the ionosphere from hours to 10 days before an EQ.
- DC electric field disturbances in the daytime and nighttime ionospheres have the same order of magnitude.
- DC electric field disturbances can reach the breakdown value during from hours to 10 days in the atmosphere at altitudes 1 to 10 km over the EQ zone.
- The quasi-stationary electric field on the Earth's surface does not exceed its background value simultaneously in the seismic area during several days.

3. Penetration of DC Electric Field Into the Ionosphere

Lithospheric activity stimulates the processes which are followed by the electric field generation. The enhancement in number density of charged aerosols by one-two orders and the increase in atmosphere radioactivity level by the injection of radon and other radioactive substances are observed during days and weeks before an EQ (Alekseev & Alekseeva, 1992; Virk & Singh, 1994; Voitov & Dobrovolsky, 1994; Heinke et al., 1995; Pulinets et al., 1997; Yasuoka et al., 2006, 2012; Omori et al., 2007; Biagi, 2009). Data on injection of the soil gases such as radon, helium, hydrogen, carbon dioxide in the surface atmosphere with horizontal spatial scale of 500 km during from several hours to several weeks before an EQ have been reported by King (1986). Igarashi et al. (1995) described the surge in five times of the radon concentration in the soil water, and the data on significant emissions of metallic aerosols Cu, Fe, Ni, Zn, Pb, Co, Cr and radon were given by Boyarchuk (1997). Quasi-static electric field disturbances in the ionosphere are observed at the same time as the injection of active substances in the lower atmosphere.

There are observed the local short-time releases of active substances along with large scale growth of the level of active substances in the lower atmosphere. They can generate the impulses of electric field near the Earth's surface, whose amplitude can reach tens kV/m but its duration does not exceed tens of minutes. A model of the generation of pulses of local electric fields with characteristic time scales of 1-10 min for the atmospheric conditions above fracture regions of EQs was considered by Liperovsky et al. (2005, 2008). They have proposed that aerosols, increased ionization velocity and upstreaming air flows occur at night-time conditions, and that water condensates at the aerosols at night when the temperature in the near-earth air is low and the relative humidity increases above earth-fracture regions. Then, the relatively large aerosol particles are mainly negatively charged, while the charge of smaller particles is overwhelmingly positive. It is assumed that aerosol clouds of small dimensions are suddenly injected into the locally heated surface atmosphere and move with the air up to higher altitudes. The vertical velocity of small particles is much smaller than that of large ones, which is equal to a few cm/s. As a consequence of the shift between the small and large particles, there occur the local pulses of the electric field in the atmosphere. The amplitude of such a field is estimated as 10^3~3×10^3 V/m, but the relaxation time of a cloud of aerosols is estimated 10 minutes. Anomalous emanation of radons preceding a large EQ was observed by Omori et al. (2007), who have analyzed atmospheric radon concentrations and estimated changes of electrical conditions in the atmosphere due to the preseismic radon anomaly. These authors used the model by Liperovsky et al. (2005), and they have shown that the radon emanation reduces the atmospheric electric field by 40%. Their estimation of field amplitude gives 10^4~10^5 V/m at the observable value of radon emanation, but unfortunately there are no calculations of electric field in the ionosphere in the above-mentioned works. Nevertheless it is assumed that this impulse electric field can be a source of lithosphere–ionosphere coupling. We should note that this impulse field is observed only in local regions. The duration of such impulses is 10 minutes, while ionospheric precursors and DC electric field in the ionosphere exist during a much longer interval of several days. The field occurs inside a dipole layer of charged aerosols cloud and the field slumps outside the dipole layer. Consequently, the local impulse electric field observed on the Earth's surface cannnot be a cause of the ionospheric effects and appearance of DC electric field in the ionosphere; that is, the radon injection in the frame of model does not affect the lithosphere–ionosphere coupling.

A generation mechanism of electric field in the lithosphere based on the result of laboratory experiments has been proposed by Freund et al. (2006, 2009) and Freund (2010). Their experiments show that when stresses are applied to one end of a block of igneous rocks, two currents flow out of the stressed rock volume. One current is carried by electrons and the other current is carried by p-holes. Positive electric potential, ionization of air molecules and corona discharge occur on the rock surface. It is assumed that air ionization is a cause of ionospheric disturbances, glows and IR emissions, but there are no calculations on the possible effect of this source to the ionosphere. This mechanism seems to be used to interpret the impulse phenomena because the source duration is over 10 minutes, but it seems to be an unlikely explanation of the existence of DC electric field over a long period of time.

Below we consider the generation mechanisms for quasi-static electric fields in the ionosphere. Spatial distribution of this field has a horizontal scale (100–1000) km and its duration is from tens hours to tens of days. The field is quasi-static if its temporal variation exceeds considerably the relaxation time (τ) of charges in the surface atmosphere τ~ε_0/σ~10~30 min (ε_0 is the permittivity of free space, and σ is the surface atmosphere conductivity). An equivalent circuit is often used to explain the generation of atmospheric electric field (Goldberg, 1984; Sapkota & Varshneya, 1990; Rycroft et al., 2000). The current flowing in the circuit is excited by a generator which is the resultant action of thunderstorms all over the world. The fair weather current density is of the order of 10^{-12} A/m^2 in the closed circuit (e.g., MacGorman & Rust, 1998; Rakov & Uman, 2002). It is assumed that the conductivity of near-Earth atmosphere of 10^{-14} S/m yield an electric field value on the Earth's surface of 10^2 V/m (Rakov & Uman, 2002). The fair weather current gives an electric field of 10^{-3} mV/m in the ionosphere with conductivity 10^{-6} S/m. Since the background electric field of magnetospheric and ionospheric origin has a value (0.1~1) mV/m in the middle-latitude ionosphere, then the field of atmospheric origin with intensity of 10^{-3} mV/m is negligible in the ionosphere. The variation of DC electric field in the ionosphere over a seismic region can be realized in two different ways. First of all one can change the load resistance and in a different way one can include an additional EMF (electro-motive force) in the global circuit.

Let us consider the first way. The processes of EQ preparing impact take place in the lower atmosphere which contributes to over 80% of load resistance of the global circuit. The injection of radioactive and chemical substances and aerosols into the atmosphere, and the variation of aerosols size and atmospheric state result in a change of load resistance. In the final analysis, all of these processes change conductivity of the surface atmosphere. In Figure 1 there is depicted the circuit with selected part of current over a seismic region. The resistance of atmosphere over thunderstorms is denoted by R_1, R_2 is the resistance of the region of thunderstorms activity, R_3 is the resistance of near-Earth atmosphere, R_i is the resistance of ionosphere, and I is the fair weather current (Rycroft et al., 2000). The load resistance R is much smaller than all of these resistances. The disturbed part of circuit (designated by red color in Figure 1) consists of the following resistances: r_1 is the resistance of upper troposphere, r_i is the resistance of ionosphere over a seismic region, and r_2 is the resistance of surface atmosphere. The disturbance of surface atmospheric conductivity results in the variation of r_2 and the electric current in this part of the circuit. For the first time, Sorokin and Yaschenko (2000) and Sorokin et al. (2001) have carried out the calculation of altitude dependence of DC electric field variation in the Earth-ionosphere layer produced by a source of ionization and a growth of conductivity in the lower atmosphere. They performed theoretical investigations of the atmospheric ionization by alpha particles and gamma quantum of the nuclear decay, and they calculated the altitude dependence of ionization rate and conductivity for different levels of radioactivity. It is shown that the electric field can be changed by 1.5-2 times in the ionosphere by the growth of conductivity in the surface atmosphere. Such a variation field does not impact onto the ionosphere because the amplitude of variations is considerably smaller than the background value. That is, the field variation is invisible in the ionosphere. This result is confirmed by Omori et al. (2008), who have shown that the quasi-static electric field is reduced by 1.5 times due to the growth of radioactivity and conductivity during the radon injection. In spite of evident results of continued unsuccessful attempts to explain the appearance of seismic-related quasi-static electric fields in the ionosphere due to the variation of conductivity in the lower atmosphere, for example, Pulinets (2009a) has assumed that an anomalous electric field in the ionosphere over an active fault occurs by the variation of conductivity in the near-earth atmosphere. The conductivity is varied due to the growth of additional radon ionization and the reduction in ions mobility by the generation of large clusters. There are missing both the proof of speculation and the calculation of field value in the ionosphere. According to Omori et al. (2007, 2008), the radon surge with magnitude 10 Bq/m_3 leads to an increase in ionization rate up to (10^6~10^7) $1/m^3s$. As a result, conductivity of the near-earth atmosphere is increased in 1.5 times, and the field is varied approximately by 1.5 times in the ionosphere as well. Since the field of fair weather in the ionosphere is 10^{-3} mV/m, then its variation by 1.5 times will be much smaller than the background value (0.1~1) mV/m. Harrison et al. (2010) have shown that an increase of ionization rate by radon in two times leads to a variation of the current flowing from the ionosphere to the Earth in 10%, and then the field is varied on the same quantity in the ionosphere. Thereby, any models based on the assumption that the ionization of lower atmosphere leads to a conclusion that the seismic-related electric field formation in the ionosphere is in apparent contradiction with experimental data that the electric field is up to 10 mV/m in the ionosphere.

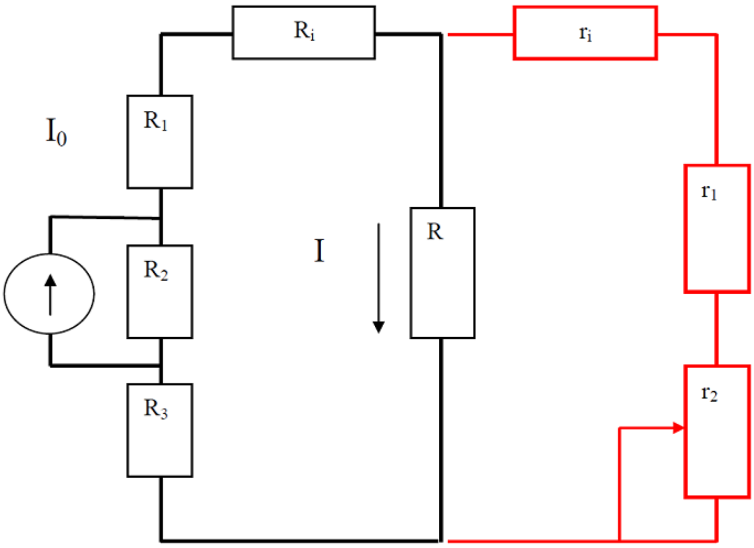

Figure 1. Equivalent electric circuit of DC electric field formation in the ionosphere over a region of conductivity disturbance in the lower atmosphere. Black color denotes the conventional global circuit, and red color indicates the part of circuit over the region of disturbed conductivity

We consider a different way of DC electric field formation in the ionosphere. The electric current and electric field are varied due to the inclusion of a seismic-related EMF in the global circuit. The EMF can be located in the lithosphere, in the atmosphere and in the vicinity of boundary between the lithosphere and atmosphere. The scheme of altitude dependence of total electric current $\mathbf{j} = \sigma\mathbf{E}+\mathbf{j}_e$ ($\mathbf{j}_e$: EMF external current) in these three cases is depicted in Figure 2. The origin of coordinate system is located on the Earth's surface. We consider the case corresponding to the left panel of Figure 2. In the frame of this model it is assumed that the EMF is located in the lithosphere and the field is transferred through the atmospheric layer with specified altitude dependent electric conductivity. The vertical component of electric field disturbance is given on the Earth's surface, and the section of closed global electric circuit is depicted in Figure 3. The uniform Ohm's law for a subcircuit without the EMF is performed in the Earth-ionosphere layer. The nature of electric field source on the Earth surface and its characteristics are not discussed in the papers based on this model. The source of field is expected to create a quasi-static electric current in the circuit for several days. The field in the ionosphere is calculated at given spatial distributions of its vertical component on the Earth's surface (Kim & Hegai, 1999; Pulinets et al., 2000, 2003; Grimalsky et al., 2003; Rapoport et al., 2004; Denisenko et al., 2008; Ampferer et al., 2010). Electric fields in the ionosphere are computed for different boundary conditions, shape and size of field horizontal distribution on the Earth's surface. Kim and Hegai (1999) showed that the field reaches (0.3~0.7) mV/m in the nighttime ionosphere if the field near the Earth has a value of 1000 V/m. Since the field in the seismic region does not exceed approximately 100 V/m (Kondo, 1968; Vershinin et al., 1999), then their calculated value of field in the ionosphere should be reduced to (0.03~0.07) mV/m. Taking into account that the conductivity of daytime ionosphere is larger than that of nighttime ionosphere by one-two order, the field value in the daytime ionosphere is approximately 10^{-3} mV/m. Calculations fulfilled in Pulinets et al. (2000, 2003) show that electric field in the nighttime ionosphere can reach (0.1~1) mV/m if it reaches a value (10^3~10^4) V/m on the Earth's surface in a seismic area with horizontal scale 100 km. This value of field on the ground surface is required to remain during several days, but such a field is unlikely to exist. Calculations performed by Denisenko et al. (2008) confirm this conclusion. It is shown that the field reaches a value 10^{-3}~10^{-4} mV/m in the ionosphere at the maximal field value E_0 = 100 V/m on the Earth surface. So, we can say that there exists, in the ionosphere, no static electric field of lithospheric origin. This can be obtained from a simple consideration of the continuity equation $\nabla\cdot\mathbf{j} = \nabla\cdot\sigma\mathbf{E} = 0$ for the vertical conductivity current $j = \sigma(z)E(z)$ in the conductive atmosphere. The estimate of maximum magnitude can be made simply in 1D (one dimensional) approximation $d\sigma E/dz = 0$. Let σ_0, σ_1 be the conductivity in the near-ground of the atmosphere and that in the ionosphere and E_0, E_1 are the electric fields near the ground and in the ionosphere, then we obtain $E_1 = E_0(\sigma_0/\sigma_1)$. Taking into account that $\sigma_0 \approx 10^{-14}$ S/m; $\sigma_1 \approx 10^{-6}$ S/m; $E_0 = 100$ V/m we find $E_1 \approx 10^{-3}$ mV/m, which is four orders of magnitude lower than the background ionospheric field. Thus the considered model is found to contradict with the well-known experimental data which indicate that the preparation processes of large magnitude EQs are accompanied by an enhancement of DC electric field in the ionosphere over the epicenter zone up to 10 mV/m.

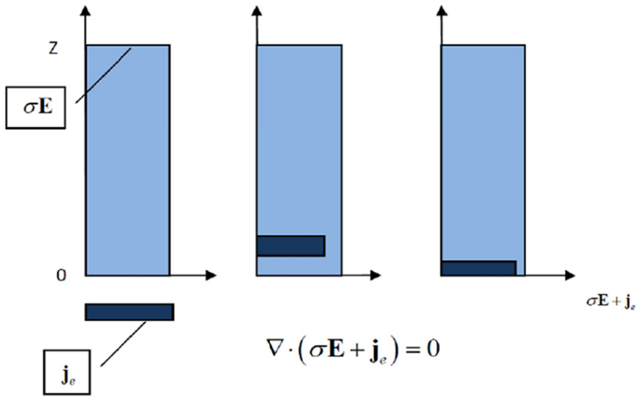

Figure 2. Dependence on altitude of the total electric current in the atmosphere. Blue figures are the conductivity current σE, and dark rectangles are the external current of EMF (electro-motive force) j_e

The case of EMF location in the atmosphere is corresponding to the middle panel of Figure 2. The same situation is expected for thunderstorms, and the penetration of the electric field of thunderstorm clouds into the ionosphere had been calculated by Park and Dejnakarintra (1973). This method was used to study the seismic-related electric field penetration in the ionosphere in several works. There is a principal difference between the phenomenon of electric field penetration into the ionosphere during thunderstorm and EQ preparation. Namely, the quasi-static electric field with magnitude up to (10^3~10^4) V/m is observed under a thunderstorm cloud (e.g., Rakov & Uman, 2002), while the field is not exceeding its background value on the surface of EQ preparing area. Therefore, the use of the above-mentioned method does not allow us to elaborate the mechanism for DC electric field penetration in the ionosphere at EQ preparing, for example, in Molchanov and Hayakawa (1996) and Pulinets et al. (2000).

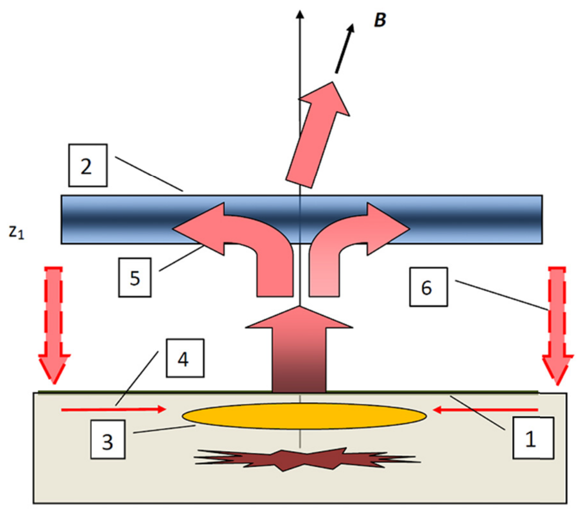

Figure 3. Model for DC electric field penetration from the lithosphere into the ionosphere. 1. Earth surface, 2. Conductive layer of the ionosphere, 3. Lithospheric source of electric field, 4. Electric field in the ground, 5. DC electric field in the ionosphere, and 6. Atmosphere-ionosphere electric circuit

It seems that the only possible way to explain results of DC electric field observation in the ionosphere over a seismic region is illustrated by the right panel of Figure 2. A principally different model which is actively developed now (Sorokin et al., 2001; Sorokin et al., 2005a; Sorokin et al., 2007; Sorokin & Chmyrev, 2010, references therein), is based on the assumption that the current source in the circuit connected with pre-EQ processes is situated not in the lithosphere or in the atmosphere, but in the near-ground atmospheric layer. The EQ preparation processes modify the atmosphere in this layer and form an EMF in the seismic zone. The additional source of electric current is generated in the global circuit at the stage of EQ preparing. The range of EMF is formed in the near-earth atmosphere and includes the boundary between the lithosphere and atmosphere. In this case the observable electric field on the surface is located inside the EMF range, and the scheme of EMF formation is depicted in Figure 4. Upward transfer of the charged aerosols by atmospheric convection and their gravitational sedimentation result in the EMF formation. Aerosols are injected into the atmosphere by soil gases with an increase in seismic activity. The external current of EMF is reduced with altitude, while the conductivity current increases with altitude, so that the total current in the circuit is constant. The value of conductivity current near the surface can be of the order of that of fair weather current, while the quantity of external current exceeds the fair weather current by four-five orders. Therefore, the conductivity current in the ionosphere is on the order of external current of EMF near the surface. Figure 5 illustrates the circuit with selected parts of current in which we included an EMF over the seismic region. Horizontal component of the electric field E_1~10 mV/m corresponds to the conductivity current flowing along the ionosphere $j \sim \sigma_1 E_1 \sim (10^{-8} \sim 10^{-7})$ A/m^2. Following Sorokin et al. (2001) the conductivity current can be 10^{-12} A/m^2 near the surface and the electric field can be 100 V/m. This fact can be understood by a simple estimation. The continuity equation for total current in the atmosphere is expressed by a form $\nabla\cdot(\sigma\mathbf{E}+\mathbf{j}_e) = 0$, where $\mathbf{j}_e$ is the EMF external current density. The simplest field estimate for the ionosphere in 1D case gives $\sigma_0 E_0 + j_{e0} = \sigma_1 E_1$. Using this equation we find $E_1 = E_0(\sigma_0/\sigma_1)(1+j_{e0}/\sigma_0 E_0)$, where j_{e0} is the density of the EMF external current near the Earth's surface. The first term on the right side of this equation corresponds to the above-mentioned model used by Kim and Hegai (1999), Pulinets et al. (2000, 2003), Denisenko et al. (2008), and Ampferer et al. (2010). If we suppose, for example, that the external current is caused by the movement of aerosols with concentration N and charge Ze under the action of vertical atmospheric convection with velocity v, then the current density can be estimated as j_{e0}~ZeNv. The aerosol charge in the atmosphere lies in the range from 100 to 800. Assuming $Z = 3\times10^2$; $N = 8\times10^9 m^{-3}$; v = 0.3 m/s, we obtain the electric field for the ionosphere: $E_1 \approx 10^{-6}(1+10^4)$ V/m ≈ 10 mVm. Thus even this rough estimate suggests that the field penetration model which has been chosen by above-mentioned authors, leads to a loss of five orders of the field magnitude in the ionosphere. The result does not depend on the way of interpolation of the altitude distribution of conductivity, so that the field penetration model used by above-mentioned authors may be wrong.

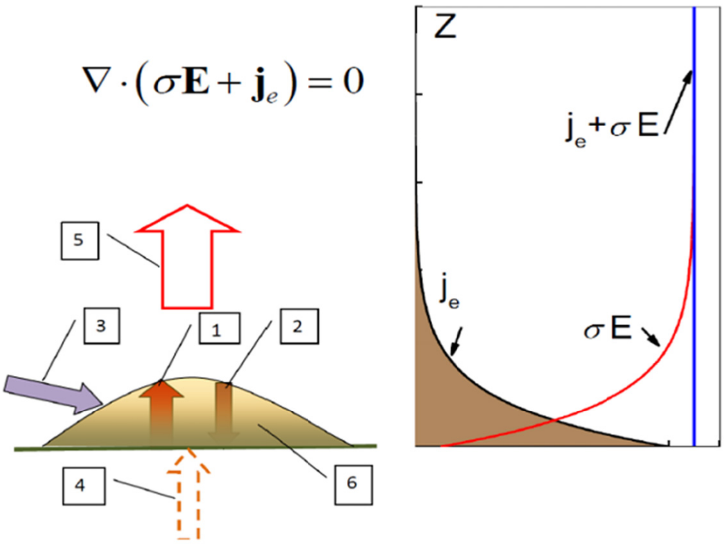

Figure 4. EMF formation in the surface atmosphere. 1. Atmospheric convection and turbulent diffusion, 2. Gravitational sedimentation, 3. Atmospheric radioactivity, 4. Soil gases, 5. Conduction electric current, and 6. External current of EMF

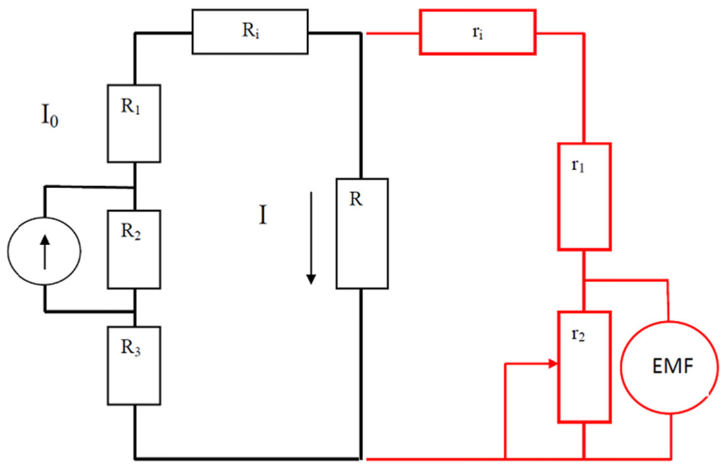

Figure 5. Equivalent circuit of DC electric field formation in the ionosphere over the region of EMF occurred in the surface atmosphere. Black color denotes the global circuit, and red color refers to the part of circuit over the region of EMF occurrence

4. Perturbation of DC Electric Field in the Atmosphere–Ionosphere Global Circuit

The formation mechanism of external current of EMF related with the dynamics of charged aerosols in the surface atmosphere has been considered in Sorokin and Yaschenko (2000) and Sorokin et al. (2001, 2007). The EMF occurs with the intensification of injection of charged soil aerosols or with the variation of meteorological conditions. Both the upward turbulent and convective transfer and gravitational sedimentation result in the quasi-static altitude distribution of aerosols density in the atmosphere. The turbulent transfer takes place due to two main reasons. The first is related with the vertical gradient of horizontal wind velocity and the transformation of wind kinetic energy into the energy of turbulent pulsations. The second is caused by the thermal instability of the atmosphere arising when the negative temperature gradient exceeds its adiabatic gradient. Turbulent vortices transfer aerosols from the altitudes where their concentration is high, to the altitudes of lower concentration. An equilibrium is attained when the vertical flux of aerosols is balanced by their gravitational sedimentation. The particle dynamics in the turbulent atmosphere can be described by the stochastic differential equations for the probability distribution function (Sorokin et al., 2001), which is the probability that a particle has the charge Ze at a moment *t* on the altitude z. Spatial and temporal dependencies of concentration of aerosols, their electric charge and external current densities are expressed as the moments of distribution function. There is obtained an estimation of the value of external current $j_e(0,t)$ near the Earth's surface $j_e(0,t) = (e\sigma_0/\varepsilon_0)(Z_+N_+ - Z_-N_-)H_j$, where e is the elementary electric charge, ε_0 is the permittivity of free space, σ_0 is the conductivity of surface atmosphere, $Z_\pm$ is the amount of positive and negative charges on aerosol, $N_\pm$ is the concentration of positive and negative charged aerosols, and H_j is the scale height of vertical distribution of external current. If we take $\sigma_0 \approx 2\times10^{-14}$ S/m, $Z_+ = 300$, $N_+ = (1\sim5)\times10^9$ 1/m^3, $H_j = (2\sim5)\times10^3$m, one obtains $j_e(0,t) \approx (10^{-6}\sim10^{-7})$ A/m^2. This value of external current of EMF shows that the mechanism discussed enables us to obtain the observed conductivity current in the ionosphere ~10^{-8} A/m^2. In many cases the injection of soil aerosols into the atmosphere is realized jointly with radioactive substances, so that the ionization increases in the atmosphere conductivity. The presence of aerosols might lead to a reduction in the conductivity due to the attachment of ions to aerosols. Moreover, the interaction of ions with aerosols changed the charge of aerosols. These effects would lead to the variation of EMF on the surface level of atmosphere. First, these processes have been studied theoretically in details by Sorokin et al. (2007), who have obtained the vertical distribution of ion production rate as a result of absorption in the atmosphere of the gamma radiation and the alpha particles from the decay of radioactive elements being constituents of the atmospheric radioactivity. An example of their computational results on the altitude dependence of ion production rate q = q(z) is depicted in Figure 6a. The parameter A is the index of growth of radioactivity in the near Earth layer. In Figure 6a they have chosen that the ion production rates due to the action of alpha particles and gamma rays are equal to each other, the background ion production rate in the atmosphere near the Earth's surface is 10^7 1/m^{3}s and the ion production rate at a maximum in the stratosphere is 4×10^7 1/m^{3}s. As follows from this plot, the vertical distribution of ion formation rate is different from the exponential altitude dependence of atmospheric radioactivity. We notice a significant increase in ion production rates in maximum. Equilibrium values of ion number densities are determined by the recombination process and the adhesion to aerosols in the atmosphere. The light singly-charged ions and the heavy ions are produced as a result of light ions adhesion to aerosols in the atmosphere near the Earth's surface. We have used the self-consistent system of nonlinear equations for the calculation of spatial distribution of external current, atmosphere conductivity and DC electric field in the Earth-ionosphere circuit at given intensity of aerosols injection and the atmosphere radioactivity. The computational result of atmospheric conductivity is depicted in Figure 6b. Conductivity depends on both the level of atmospheric radioactivity and the number density of aerosols, and we have chosen the value of aerosols concentration in the surface atmosphere equal to 2×10^9 1/m^3. Calculations show that the growth of radioactivity level in the surface atmosphere results in an increase in conductivity and the growth of aerosols concentration results in a reduction in conductivity due to the loss of light ions attached to aerosols.

Sorokin et al. (2007) have shown that the external current of EMF is defined on the atmospheric conductivity layer and the electric field is generated by its vertical component on the near-Earth level. As it is noted above, the significant (up to 1 kV/m) pre-EQ vertical electric fields on the Earth's surface have the characteristic temporal scale of the order of tens of minutes. At the same time the atmospheric electric field variations with typical scale exceeding 1 day at the distances within hundreds to thousands km from the EQ center during a seismically active period are characterized by the magnitude not exceeding ~100 V/m. The cause of such a limitation can be explained in terms of the mechanism of feedback between the disturbances of vertical electric field and the causal external currents on the Earth's surface. Such a feedback is caused by the formation of a potential barrier on the ground-atmosphere boundary at the passage of upward moving charged aerosols through this boundary. Their upward movement is performed due to the viscosity of soil gases flowing into the atmosphere. If, for example, a positively charged particle goes from the ground to the atmosphere, the Earth's surface is charged negatively. So, the downward electric field prevents more particles from penetration through the surface. At the same time this field stimulates the going out on the surface of the negatively charged particles. In the presence of such coupling the magnitude of external currents on the Earth's surface depends on the vertical component of the electric field on the surface. The first study of the mechanism of this field limitation (Sorokin et al., 2005a, 2007) yields that the value of vertical component of quasi-static electric field does not exceed a maximal value of the order of 90 V/m at any amount of external current of EMF. The self-consistent equation for the external current and electric field has been derived first by Sorokin et al. (2007). An example of those calculation results of altitude distribution of external current with taking into account the feedback with electric current is depicted in Figure 6c. It is shown that the external current is generally located at the altitudes up to 10 km and its value can be (10^{-8}~10^{-6}) A/m^2.

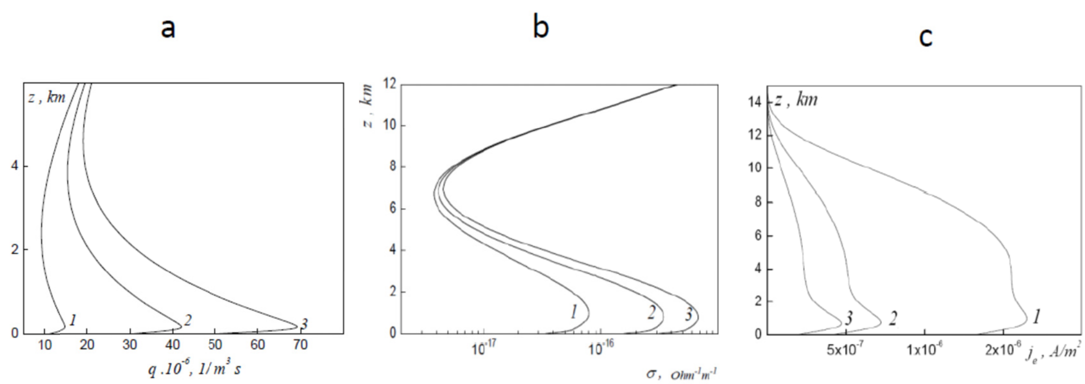

Figure 6. Computational results by a self-consistent system of non-linear equations (Sorokin et al., 2007). a) Vertical distribution of the ion production rate, b) Altitude profiles calculated for the atmosphere conductivity over the center of disturbed area, and c) Altitude dependences of external electric current over the center of disturbed region. Curves 1, 2 and 3 correspond to different levels of atmospheric radioactivity (A is the index of radioactivity growth in the near-Earth layer) 1. A=0, 2. A=2, 3. A=4

The theory of generation of the seismic-related DC electric field conforming to both the direct and indirect observation data of fields in the ionosphere is elaborated first by Sorokin et al. (2001, 2005a, 2007) and Sorokin and Chmyrev (2010). The field is associated with electric current disturbances flowing in the global electric circuit. The source of current disturbances is the EMF included in the global circuit, which is generated by the injection of charged aerosols into the atmosphere and their upward transfer and gravitational sedimentation. The scheme of the formation of electric current disturbance in the global circuit is presented in Figure 7. The self-consistent system of nonlinear equation to compute the spatial distribution of external current, electric field, atmosphere conductivity, concentration of ions and charged aerosols is included in the theory (Sorokin et al., 2005b). Figure 8 presents an example of their calculation of spatial distribution of electric field in the ionosphere and on the Earth`s surface. Horizontal distribution of external current on the surface is chosen to be ellipse-like with axis directed under an angle to the meridian plane. These two figures illustrate that the horizontal electric field in the ionosphere reaches ~10 mV/m, while the vertical electric field on the Earth's surface is limited by a magnitude ~ 90 V/m over an active fault. Another important result is that DC electric field in the ionosphere has maximal magnitudes at the edges of area of external current. The horizontal scale of vertical electric field enhancement on the ground exceeds the characteristic horizontal scale of external current. Within this area the vertical field practically does not depend on distance. These calculations show that the field component in the meridian plane strongly depends on the magnetic field inclination.

Investigation of the spatial distribution of electric field in the atmosphere connected with disturbances of current in the global circuit based on the above-mentioned theory has been carried out by Sorokin et al. (2011, 2012a, 2012b), who have shown that the DC electric field at the certain conditions can reach the breakdown value in the troposphere. Figure 9 illustrates the spatial distribution of electric field normalized by the breakdown value for the axial symmetric horizontal distribution of external current with horizontal spatial scale 100 km on the surface. It is possible to expect occurrence of the one or two levels with thickness (1~2) km located at different altitudes (5~10) km in which the electric field reaches a breakdown value. Characteristics of these levels depend on the parameters of atmosphere and aerosols.

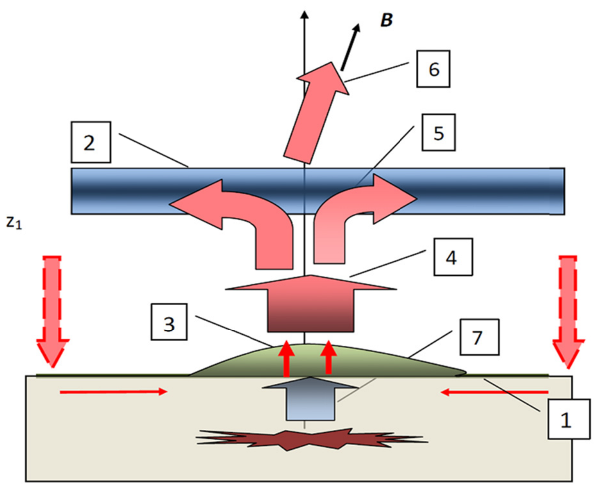

Figure 7. Model of DC electric field generation in the ionosphere by seismic related EMF (electro-motive force) in the lower atmosphere (Sorokin et al., 2005a). 1. Earth surface, 2. Conductive layer of the ionosphere, 3. External electric current of EMF in the surface atmosphere, 4. Conductivity electric current in the atmosphere–ionosphere circuit, 5. DC electric field in the ionosphere, 6. Field-aligned electric current, and 7. Charged aerosols injected into the atmosphere by soil gases

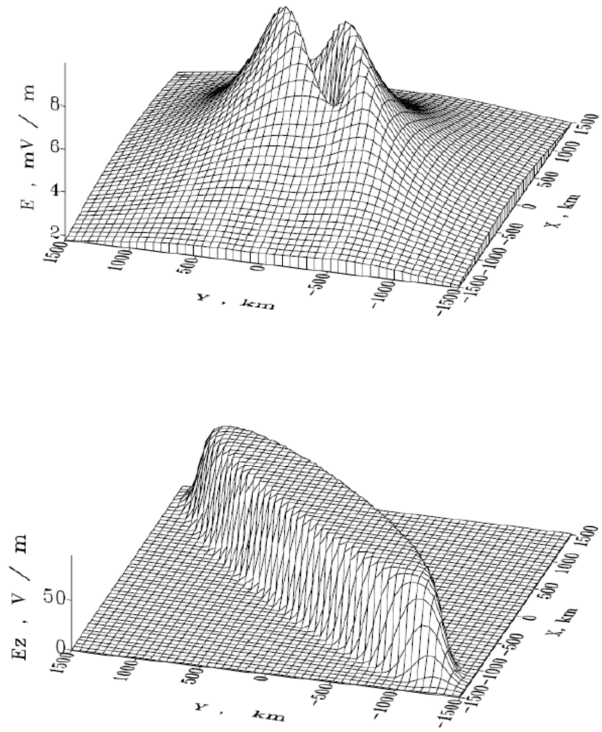

Figure 8. Spatial distributions of horizontal electric field in the ionosphere (upper panel) and vertical electric field near the Earth surface (bottom panel) over the ellipsoidal fault (Sorokin et al., 2006). The angle of fault axis orientation to the meridian plane is $\beta = 45^{\circ}$. The angle of magnetic field inclination is $\alpha = 20^{\circ}$

According to the above-mentioned calculations, the DC electric field can reach 10 mV/m in the ionosphere even if the field magnitude does not exceed 100 V/m on the Earth's surface. The theory of DC electric field amplification and penetration into the ionosphere is based on the following issues.

1) The electric field in the ionosphere and on the Earth's surface is a field of conductivity current flowing in the atmosphere-ionosphere circuit.
2) The source of conductivity current is an external current of EMF included in this circuit.
3) The EMF is formed by convective transport of the charged aerosols and the radioactive elements which are injected along with soil gases from the lithosphere into the lower atmosphere.
4) The field limitation on the Earth surface is caused by a feedback mechanism between the excited electric field and the causal external current. This feedback is produced by the potential barrier for charged particle at its transfer from the ground to the atmosphere.

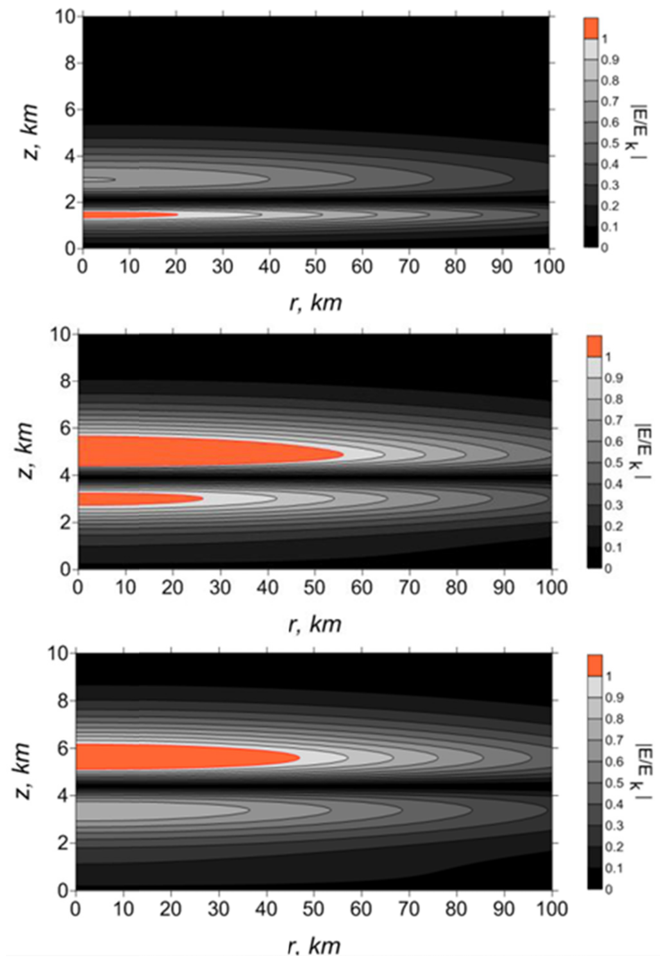

Figure 9. Examples of spatial distribution of DC electric field magnitude in the lower atmosphere normalized to the breakdown electric field (Sorokin et al., 2011)

5. LAI Coupling Models

In order to understand the nature of numerous ionospheric and electromagnetic EQ precursors, it is necessary to study the physical processes and then to create the model of seismicity impact to the ionosphere plasma or LAI coupling mechanism. At the present time we consider that this impact is realized generally by the two major hypotheses, (i) internal gravity waves (IGW) or (ii) electric field (see Hayakawa et al., 2004; Molchanov & Hayakawa, 2008; Pulinets & Ouzounov, 2011; Kuo et al., 2011).

Though we do not go into the details of the former channel, we make a brief description on this channel. Gokhberg and Shalimov (2000) gave the analyses of experimental data obtained at the final stage of EQ preparing, who considered the ionospheric perturbations developing as ionospheric irregularities for several days before strong EQs. Those authors believed that the occurrence of these irregularities is connected with IGW propagation through the ionosphere. Their source could be the long wave earth oscillations, local green gas effect or an unsteady injection of lithospheric gases, but the more effective mechanism is the growth of lithospheric gas emanation into the atmosphere. They suppose that the IGW generation should be considered as a mechanism of LAI coupling because the atmosphere stratification favors the wave amplification as it propagates upward. Further they discussed various likely scenarioes of the accompanying processes developing in the ionosphere. Molchanov et al. (2004) and Molchanov (2009) presented recently a general concept of the role of IGW in the LAI coupling. The atmospheric perturbation of temperature and density could follow preseismic hot water/gas releases resulting in the generation of atmospheric gravity waves (AGW) with periods in a range of 6-60 min. Seismo-induced AGW could lead to the modification of ionospheric turbulence (Molchanov, 2009) and to the change of the-over-the horizon VHF radio wave propagation in the atmosphere (Devi et al., 2012), perturbations of VLF/LF waves in the lower ionosphere (Rozhnoi et al., 2004, 2005; Hayakawa et al., 2010) and the depression of ULF emissions on the ground (Schekotov et al., 2006). There are some difficulties in the interpretation of observational results of EQ precursors based on the model of IGW propagation. One of them is as follows. These waves are propagated angularly to the Earth's surface, and the angle increases depending on wave period. So, IGW reaches the ionosphere at a distance of the order of 1000 km from the EQ epicenter, which seems to be in conflict with the localization of the plasma and electromagnetic disturbances in the vicinity of EQ epicenter. Though there have been recently published a few papers suggesting the important role of AGW channel in the LAI coupling (Korepanov et al., 2009; Hayakawa et al., 2011a), in which you can find a summary of recent findings in favor of this hypothesis.

Below we consider the mechanism of the influence of seismic-related electric fields on the ionosphere. The model of LAI coupling was described in Pulinets et al. (2000), which consists of two stages which are not related with each other. They considered the formation of electric field in the near-ground atmosphere due to the appearance of metallic aerosols and ionization source. The source of ionization produces positive and negative ions, and then heavy ions are formed by adhesion of water molecules to the light ions. They calculated the altitude dependence of electric field caused by diffusion, transfer of ions and aerosols by the electric field, gravitational sedimentation of the heavy particles and upward moving of the light particles by the atmosphere convection. The interaction between ions with different signs and their adhesion to the aerosols are taken into account. Their calculations show that during 50 seconds after the turning on the ionization source there is formed an electrode layer up to 30 cm altitude. The number density of the positive and negative ions is different and the electric field is reduced in 1.5 times in this layer. The value of electric field grows in three times above this layer. As they show that this mechanism could be used to explain the electric field variation at fog occurring in the near-ground level. Further, those authors gave a solution of the problem on the electric field penetration into the ionosphere through the conducting atmosphere with exponentially upward increasing conductivity. By imposing the boundary condition on the horizontal distribution of vertical component of electric field on the Earth's surface, they calculated the horizontal component of electric field at the altitude 90 km based on the spatial scale of horizontal distribution of electric field on the Earth's surface. Obviously, the ionosphere conductivity in night time is less than that in day time, so that the electric field at night will be more enhanced than at day. Their calculation shows that even though the radius of disturbed region is 200 km and the field on the ground is 100 V/m, the magnitude of electric field will be 0.07 mV/m. This field is likely to be much smaller than the background field in the ionosphere and consequently it cannot have any effect on the ionosphere. Further those authors conclude that if the field on the ground will be 1000 V/m, then the effect of this field on the ionosphere will be possible. However, such a field in the seismic region with radius 200 km is considered to be implausible. So the above-mentioned work cannot be a basis of LAI coupling model.

Pulinets (2009b) has then made an attempt to explain the possible ionosphere modification due to the atmospheric ionization during the radon injection in the vicinity of active faults. The process of local modification of global electric circuit and the ionosphere variability for tectonic activity is discussed. He supposes that the occurrence of any additional source of ionization has a double effect on the atmosphere conductivity. The appearance of additional ions increases the atmosphere conductivity, while the generation of heavy cluster ions leads to its reduction. However, there is no estimation on the resultant value of conductivity. Further the author supposes that the anomaly of atmosphere conductivity leads to the variation of electric current in the local part of the global circuit, but no calculation of this field has been performed. One should keep in mind that there are theoretical investigations of the atmosphere conductivity modification during the course of ionization. In application to the seismic effect Sorokin et al. (2007) studied in details the processes of conductivity formation during the course of gamma and alpha decay based on the solution of a system of self-consistent nonlinear equations for electric field, atmosphere conductivity, density of ions and aerosols with taken into account their interaction. The well-known value of fair weather current is $\sim 10^{-12}$ A/m^2 and atmosphere conductivity is $\sim 10^{-14}$ mho/m, then the field on the ground has a value of ~100 V/m. The value of ionosphere conductivity is $\sim 10^{-6}$ mho/m, so that the field in the ionosphere for the current with the same density has a value of $\sim 10^{-3}$ mV/m. The variation of conductivity in the near-ground atmosphere due to the ionization in two times results in the variation of current density of the same order in the local part of circuit. So that, this additional electric field is on three-four orders less than the ionospheric field and its effect on the ionosphere and equatorial anomaly is negligible. Therefore, the hypothesis suggested is physically not well grounded and it cannot be a candidate for the creation of LAI coupling mode. On this reason the suggestion by Pulinets (2009b) is in contradiction with results obtained by Klimenko et al. (2012), who show that observed disturbances of TEC occur on the assumption that DC electric field reaches (3~9) mV/m in the ionosphere. After all, they use the work by Pulinets (2009b) to interpret the data in spite of the contradiction with obtained results.

A principally alternative physical idea based on the electrodynamic model of plasma and electromagnetic disturbances accompanying the processes of EQ preparing was developed in Sorokin et al. (2001, 2007) and Sorokin and Chmyrev (2010). First, this model allowed them to explain the results of observation of quasi-static electric field both in the ionosphere and on the Earth's surface in the seismic region, because other models could not explain the nature of such a field. In the frame of this model they found the mechanism for the enhancement of conducting electric current with altitude and the mechanism for limitation of electric field vertical component on the ground surface. The enhancement mechanism is realized by a decrease with altitude of EMF external current at the condition of conservation of the total current. This current is equal to the sum of conductivity and external currents. The external current of EMF is formed in the near ground atmosphere, as seen in Figure 5. In this case even at the growth in conductivity with altitude the field can reach an amplitude of 10 mV/m in the ionosphere. While the conductivity current is appeared by including an additional EMF in the global circuit. The EMF is formed during the injection of charged aerosols by soil gases in the atmosphere and their transfer in the convective atmosphere. The field is limited by a feedback between the external current of EMF and the electric field generated near Earth's surface. Calculations show that the amplitude of disturbed electric field does not exceed their background value on the Earth's surface. In one sense the above-mentioned model is similar to the model of AGW influence to the ionosphere, because the amplitude of AGW grows with altitude by a decrease in atmosphere density. By analogy, the value of conductivity current grows with altitude by a decrease of external current. This implies that the effects are becoming stronger in the ionosphere, but it is difficult to identify AGWs above the background in the near-ground atmosphere. Similarly it is difficult to select the disturbances of conductivity current because their amplitude on the ground does not exceed the background value which is equal to the fair weather current. Both of these effects have a unified source which are lithospheric gases injected into the atmosphere. One can suppose that both AGW and electric current can affect the ionosphere simultaneously, though the consequences of these effects can be different.

According to the electrodynamic model, the growth of electric field in the ionosphere is caused by the EMF formation and the corresponding variation of electro-physical characteristics of lower atmosphere as a result of injection of soil gases, aerosols and radioactive substances during EQ preparation. In the frame of our model, the theory of generation of quasi-static electric field in the atmosphere–ionosphere system was developed, and the methods for calculation of electric field spatial distribution were elaborated. Sorokin et al. (2001, 2005a, 2006a, 2007) and Sorokin and Chmyrev (2010) carried out the theoretical investigation of mechanisms of EMF formation in the lower atmosphere, who have shown that the quasi-static electric field reaches 10 mV/m in the ionosphere while their value is of the order of 100 V/m on the Earth's surface. Moreover, the field can reach a breakdown value in the layer with thin 1-2 km on the altitudes 5-10 km in the troposphere (Sorokin et al., 2011, 2012a, b). Value of the external current of EMF can be approximately 10^{-8}~10^{-6} A/m^2 near the ground. They have further investigated theoretically plasma and electromagnetic effects accompanying the generation of conducting current in the global circuit, and have shown that the appearance of EMF in the global circuit leads to the stimulation of a set of observed plasma and electromagnetic phenomena. An enhancement of the electric field might result in the instability of AGWs in the ionosphere (Sorokin et al., 1998), but the exponential growth of AGW amplitude by the electric field in the ionosphere is limited by vortex formation (Chmyrev & Sorokin, 2010). As a result, the horizontal irregularities of conductivity with scale of approximately 10 km are expected to take place in the E layer of ionosphere. This process is accompanied by field-aligned currents and plasma irregularities stretched along magnetic field lines in the upper ionosphere (Sorokin et al., 1998; Sorokin et al., 2000). Their appearance leads to ULF oscillations (Sorokin et al., 1998) and spectral broadening of VLF transmitter signals (Chmyrev et al., 2008) registered on satellites. The scattering of background electromagnetic emissions by horizontal irregularities of conductivity in the lower ionosphere results in the enhancement of electromagnetic ELF emissions registered on satellites (Borisov et al., 2001) and generation of gyrotropic waves propagated along E layer of the ionosphere. Their propagation forms line spectra of ULF oscillations (Sorokin et al., 2003; Sorokin & Hayakawa, 2008; Sorokin et al., 2009) and the change of resonance frequency of Schuman resonances (Hayakawa et al., 2005, 2011b). Moreover, the appearance of irregularities in the nighttime ionosphere leads to depressions of ULF pulsations of magnetosphere origin (Sorokin et al., 2004; Schekotov et al., 2006; Hayakawa et al., 2013). The growth of electric field up to the breakdown value is caused by random electric discharges, which might generate VHF radio emission in the troposphere over the EQ epicenter (Sorokin et al., 2011, 2012a, b). The generation of conductivity current in the global circuit is accompanied by the modification of ionosphere. Perturbations in the D region of the ionosphere may be generated by both the transfer of charged particles and electron heating (Laptukhov et al., 2009). The electrons are in the upper part of D layer and negative charged ions are in the bottom part of D layer which occurs by quick adhesion of electrons to the neutral molecules. The layer with much density of electrons is appeared in the D region by the transferring charged particles and changing the type of charge carrier by the electric current flowing. The enhancement of electric current which flows from the atmosphere to the ionosphere results in the growth of plasma density in the E region and sporadic layer formation (Sorokin et al., 2006b). Modification of F region and growth of light ions density are caused by heating release due to the electric current flow in the E region of ionosphere (Sorokin & Chmyrev, 1999). Theoretical investigations of above-mentioned phenomena are accompanied by the calculation of observed parameters and their comparison with experimental data. The lithosphere, atmosphere and ionosphere are an integrated environment in which physical phenomena are related with each other. According to the above-mentioned model, the intensive processes in the lithosphere and atmosphere are the cause of electrodynamic effect onto the ionospheric plasma. Figure 10 illustrates the scheme of processes and registered parameters consisting of electrodynamic model of atmosphere–ionosphere coupling. The left units denote processes stimulated by local current disturbances of global circuit, and the right units denote parameters observed by both satellite and ground-based methods. The injection of charged aerosols by soil gases in the atmosphere forms an additional EMF in the global circuit. Inclusion of the EMF in this circuit leads to the above-mentioned different phenomena.

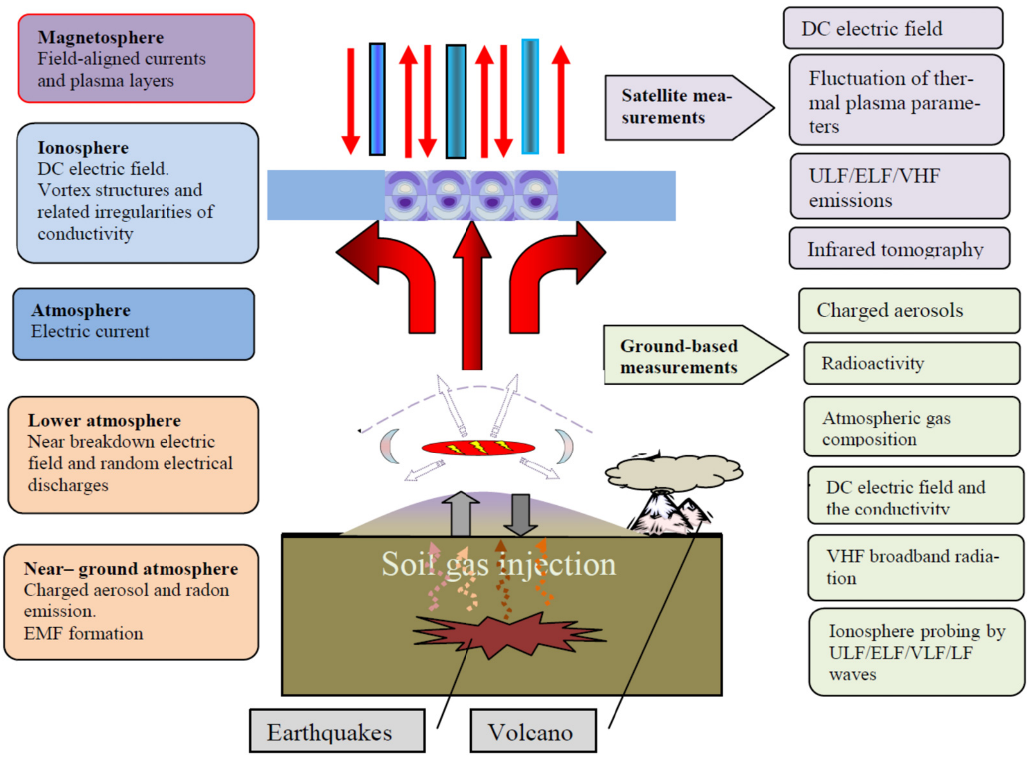

Figure 10. The scheme of electrodynamic model of atmosphere–ionosphere coupling

6. Conclusions

Satellite-and ground-based observations of DC electric field over a seismic region show that its amplitude reaches 10 mV/m in the ionosphere, the field reaches a breakdown value in the lower atmosphere, but, at the same time, it does not exceed the background value on the Earth`s surface. These disturbances occupy the region with a horizontal spatial scale from hundreds to thousands km over the seismic region during several days before an EQ. Critical review of existing models has allowed us to rule out the models which are in contradiction with above-mentioned experimental data. It seems that any models based on the assumption that the quasi-static electric field in the ionosphere occurred due to both the variation of atmospheric conductivity by radon injection and transfer of field given on the Earth surface are definitely in contradiction with the experimental data, so that these models cannot be a possible candidate of lithosphere-ionosphere coupling mechanism. Because it is impossible to explain the growth of electric field up to 10 mV/m in the ionosphere area with horizontal scale (100-1000) km and, at the same time, to explain the absence of visible field variation on the Earth’s surface. The field penetration models lead to the loss of five orders of the field magnitude in the ionosphere in comparison with experimental data.

This review suggests that there is only one possible way to satisfactorily explain the results of DC electric field observation in the ionosphere and in the atmosphere over a seismic region and on the ground. A principally different model is based on the assumption that the current source in the circuit connected with pre-EQ processes are situated not in the lithosphere or in the atmosphere, but in the near-ground atmospheric layer. The EQ preparation processes modify the atmosphere in this layer and form an EMF in the seismic zone. The additional source of electric current is generated in the global circuit at the stage of EQ preparing. The range of EMF is formed in the near-earth atmosphere and includes the boundary between the lithosphere and atmosphere. In this case the observable electric field on the surface is located inside the EMF range. Upward transfer of the charged aerosols by atmospheric convection and their gravitational sedimentation result in the EMF formation. Aerosols are injected into the atmosphere by soil gases during an increase in seismic activity. The external current of EMF is reduced with altitude while the current of conductivity increases with altitude, so the total current in the circuit is constant. The value of conductivity current near the surface can be of the order of the value of fair weather current, while the external current exceed the conductivity current by four–five orders. Therefore, conductivity current in the ionosphere is on the order of the external current of EMF near the surface.

The above-mentioned model is similar to the model for AGW influence to the ionosphere, because the amplitude of AGW grows with altitude by decreases of atmosphere density. By analogy, the value of conductivity current increases with altitude by decreases of external current. This implies that the effects become stronger in the ionosphere, but it is difficult to identify any AGW above the background in the near ground atmosphere. So that, it is difficult to identify the disturbances of conductivity current on the ground because their amplitude does not exceed the background value which equals the fair weather current. Both of these effects have a unified source which is injected lithospheric gases in the atmosphere, since one can suppose that both AGW and electric current can affect the ionosphere simultaneously. Lithosphere, atmosphere and ionosphere are an integrated environment in which physical phenomena are related with each other. On the basis of the above-mentioned model the intensive processes in the lithosphere and atmosphere such as EQs, volcanoes, typhoons, thunderstorms are the cause of electrodynamic effect onto the ionospheric plasma. All of these processes are accompanied by numerous electromagnetic and plasma phenomena, which will be discussed elsewhere.

References

Afonin, V. V., Molchanov, O. A., Kodama, T., Hayakawa, M., & Akentieva, O. A. (1999). Statistical study of ionospheric plasma response to seismic activity: search for reliable result from satellite observations. In M. Hayakawa (Ed.), *Atmospheric and Ionospheric Electromagnetic Phenomena Associated with Earthquakes* (pp. 597-617). Tokyo, Japan: Terra Scientific Publishing Company (TERRAPUB).

Alekseev, V. A., & Alekseeva, N. G. (1992). Investigation of metal transfer in the biosphere during gaseous emission in zones of tectonic activity using methods of nuclear physics. *Nucl. Geophys., 6*, 99-105.

Alperovich, L. S., Gokhberg, M. B., Sorokin, V. M., & Fedorovich, G. V. (1979). On generation of the geomagnetic variation by acoustic oscillations occurring in time of earthquake. *Transaction of USSR Academy of Sciences, Physics of the Earth, 3*, 58-68.

Ampferer, M., Denisenko, V. V., Hausleitner, W., Krauss, S., Stangl, G., Boudjada, M. Y., & Biernat, H. K. (2010). Decrease of the electric field penetration into the ionosphere due to low conductivity at the near ground atmospheric layer. *Annales Geophysicae, 28*, 779-787. http://dx.doi.org/10.5194/angeo-28-779-2010

Biagi, P. F. (2009). Pre and post seismic disturbances revealed on the geochemical data collected at Kamchatka (Russia) during the last 30 years. In M. Hayakawa (Ed.), *Electromagnetic Phenomena Associated with Earthquakes* (pp. 97-117). Trivandrum, India: Transworld Research Network.

Borisov, N., Chmyrev, V., & Rybachek, S. (2001). A new ionospheric mechanism of electromagnetic ELF precursors to earthquakes. *J. Atmos. Solar-Terr. Phys., 63*, 3-10. http://dx.doi.org/10.1016/S1364-6826(00)00153-X

Boskova, J., Smilauer, I., Triska, P., & Kudela, K. (1994). Anomalous behaviour of plasma parameters as observed by the Intercosmos-24 satellite prior to the Iranian earthquake of 20 June 1990. *Studia Geophys. Geodet., 8*, 213-220. http://dx.doi.org/10.1007/BF02295915

Boyarchuk, K. A. (1997). Kinetics of elementary ions in the lower atmosphere acted upon by ionizing radiation. *Proc. Russian Acad. Sci., Atmos. Ocean. Phys., 33*(2), 236-240.

Buchachenko, A. L., Oraevsky, V. N., Pokhotelov, O. A., Strakhov, V. N., Sorokin, V. M., & Chmyrev, V. M. (1996). Ionosphere earthquake precursors. *Usp. Fiz. Nauk, 166*(9), 1023-1029. http://dx.doi.org/10.3367/UFNr.0166.199609g.1023

Chmyrev, V. M., Isaev, N. V., Bilichenko, S. V. & Stanev, G. A. (1989). Observation by space - borne detectors of electric fields and hydromagnetic waves in the ionosphere over on earthquake center. *Phys. Earth Planet. Inter., 57*, 110-114. http://dx.doi.org/10.1016/0031-9201(89)90220-3

Chmyrev, V. M., Isaev, N. V., Serebryakova, O. N., Sorokin, V. M., & Sobolev, Y. P. (1997). Small-scale plasma inhomogeneities and correlated ELF emissions in the ionosphere over an earthquake region. *J. Atmos. Solar-Terrr. Phys., 59*, 967-974.

Chmyrev, V. M., Sorokin, V. M., & Shklyar, D. R. (2008). VLF transmitter signals as a possible tool for detection of seismic effects on the ionosphere. *J. Atmos. Solar - Terr. Phys., 70*, 2053-2060. http://dx.doi.org/10.1016/j.jastp.2008.09.005

Chmyrev, V. M., & Sorokin, V. M. (2010). Generation of internal gravity vortices in the high-latitude ionosphere. *J. Atmos. Solar-Terr. Phys., 72*, 992-996. http://dx.doi.org/10.1016/j.jastp.2010.05.013

Denisenko, V. V., Boudjada, M. Y., Horn, M., Pomozov, E. V., Biernat, H. K., Schwingenschuh, K., … Cristea, E. (2008). Ionospheric conductivity effects on electrostatic field penetration into the ionosphere. *Natural Hazards Earth Syst. Sci., 8*, 1009-1017. http://dx.doi.org/10.5194/nhess-8-1009-2008

Devi, M., Barbara, K., Ruzhin, Y. Y., & Hayakawa, M. (2012). Over-the-horizon anomalous VHF propagation and earthquake precursors. *Survey Geophys., 33*, 1081-1106. http://dx.doi.org/10.1007/s10712-012-9185-z

Fitterman, D. V. (1979). Theory of electrokinetic-magnetic anomalies in a faulted half–space. *J. Geophys. Res., 84*, 6031-6040. http://dx.doi.org/10.1029/JB084iB11p06031

Fraser-Smith, A. C., Bernardi, A., McGill, P. R., Ladd, M. E., Helliwell, R. A., & Villard, O. G. Jr. (1990). Low-frequency magnetic field measurements near the epicenter of the Ms=7.1 Loma Prieta earthquake. *Geophys. Res. Lett., 17*, 1465-1468. http://dx.doi.org/10.1029/GL017i009p01465

Freund, F. (2010). Toward a unified solid state theory for preearthquake signals. *Acta Geophysica, 58*(5), 719-766. http://dx.doi.org/10.2478/s11600-009-0066-x

Freund, F. T., Kulahci, I. G., Cyr, G., Ling, J., Winnick, M., Tregloan-Reed, J., & Freund, M. M. (2009). Air ionization at rock surfaces and pre-earthquake signals. *J. Atmos. Solar-Terr. Phys., 71*, no. 17-18, 1824-1834. http://dx.doi.org/10.1016/j.jastp.2009.07.013

Freund, F. T., Takeuchi, A., & Lau, B. (2006). Electric currents streaming out of stressed igneous rocks-A step towards understanding pre-earthquake low frequency EM emissions. *Phys. Chem. Earth, 31*, 389-396. http://dx.doi.org/10.1016/j.pce.2006.02.027

Fukumoto, Y., Hayakawa, M., & Yasuda, H. (2001). Investigation of over-horizon VHF radio signals associated with earthquakes. *Natural Hazards Earth Syst. Sci., 1*, 107-112. http://dx.doi.org/10.5194/nhess-1-107-2001

Galperin, Yu. I., Gladyshev, V. A., Dzhordzhio, N. V., Larkina, V. I., & Mogilevsky, M. M. (1993). Precipitation of high-energy captured particles in the magnetosphere above the epicenter of an incipient earthquake. *Cosmic Research, 31*, 72-89.

Gladyshev, V., & Fishkova, L. M. (1994). Optical research of seismoactivity. In M. Hayakawa & Y. Fujinawa (Eds.), *Electromagnetic Phenomena Related to Earthquake Prediction* (pp. 35-42). Tokyo, Japan: Terra Scientific Publishing Company, TERRAPUB.

Gokhberg, M. B., Morgunov, V. A., & Pokhotelov, O. A. (1988). *Seismoelectromagnetic Phenomena*. Moscow, Russia: Nauka, p. 173.

Gokhberg, M. B., Nekrasov, A. K., & Shalimov, S. L. (1996). On influence of greenhouse gases instable injection to the ionosphere in seismic active regions. *Transaction of USSR Academy of Sciences, Physics of the Earth, 8*, 52-59.

Gokhberg, M. B., & Shalimov, L. S. (2000). Lithosphere-ionosphere coupling and their modelling. *Russian J. Terrestrial Sciences, 2*(2), 95-108.

Goldberg, R. A. (1984). Middle atmospheric electrodynamics: status and future. *J. Atmos. Terr. Phys., 46*, 1083-1101. http://dx.doi.org/10.1016/0021-9169(84)90010-2

Gorbatikov, A. V., Molchanov, O. A., Hayakawa, M., Uyeda, S., Hattori, K., Nagao, T., … Maltsev, P. (2002). Acoustic emission possibly related to earthquakes, observed at Matsushiro, Japan and its implications. In M. Hayakawa & O. A. Molchanov (Eds.), *Seismo Electromagnetics: Lithosphere-Atmosphere-Ionosphere Coupling* (pp. 1-10). Tokyo, Japan: TERRAPUB.

Gousheva, M., Danov, D., Hristov, P., & Matova, M. (2008). Quasi-static electric fields phenomena in the ionosphere associated with pre- and post earthquake effects. *Natural Hazards Earth Syst. Sci., 8*, 101-107. http://dx.doi.org/10.5194/nhess-8-101-2008

Gousheva, M., Danov, D., Hristov, P., & Matova, M. (2009). Ionospheric quasi-static electric field anomalies during seismic activity August-September 1981. *Natural Hazards Earth Syst. Sci., 9*, 3-15. http://dx.doi.org/10.5194/nhess-9-3-2009

Gousheva, M., Glavcheva, R., Danov, D., Angelov, P., Hristov, P., Kirov, B., & Georgieva, K. (2006). Satellite monitoring of anomalous effects in the ionosphere probably related to strong earthquakes. *Adv. Space Res., 37*, 660-665. http://dx.doi.org/10.1016/j.asr.2004.12.050

Grimalsky, V. V., Hayakawa, M., Ivchenko, V. N., Rapoport, Yu. G., & Zadorozhnii, V. I. (2003). Penetration of an electrostatic field from the lithosphere into the ionosphere and its effect on the D-region before earthquakes. *J. Atmos. Solar-Terr. Phys., 65*, 391-407. http://dx.doi.org/10.1016/S1364-6826(02)00341-3

Hao, J. G. (1989). Near earth surface anomalies of the atmospheric electric field and earthquakes. *Acta Seismol. Sinica, 2*, 289-298.

Hao, J., Tang, T., & Li, D. (2000). Progress in the research of atmospheric electric field anomaly as an index for short-impending prediction of earthquakes. *J. Earthquake Pred. Res., 8*, 241-255.

Harrison, R. G., Aplin, K. L., & Rycroft, M. J. (2010). Atmospheric electricity coupling between earthquake regions and the ionosphere. *J. Atmos. Solar-Terr. Phys., 72*, 376-381. http://dx.doi.org/10.1016/j.jastp.2009.12.004

Hayakawa, M. (Ed.). (2009). *Electromagnetic Phenomena Associated with Earthquakes.* p. 279. Trivandrum, India: Transworld Research Network.

Hayakawa, M. (Ed.). (2012). *The Frontier of Earthquake Prediction Studies*. p. 794. Tokyo, Japan: Nihon-senmontosho-Shuppan.

Hayakawa, M., & Hobara, Y. (2010). Current status of seismo-electromagnetics for short-term earthquake prediction. *Geomatics, Natural Hazards and Risk, 1*(2), 115-155. http://dx.doi.org/10.1080/19475705.2010.486933

Hayakawa, M., Hobara, Y., Ohta, K., Izutsu, J., Nickolaenko, A. P., & Sorokin, V. M. (2011b). Seismogenic effects in the ELF Schumann resonance band. *IEEJ Transactions on Fundamentals and Materials, 131*(9), 684-690. http://dx.doi.org/10.1541/ieejfms.131.684

Hayakawa, M., Kasahara, Y., Nakamura, T., Muto, F., Horie, T., Maekawa, S., …, Molchanov, O. A. (2010). A statistical study on the correlation between lower ionospheric perturbations as seen by subionospheric VLF/LF propagation and earthquakes. *J. Geophys. Res., 115*, A09305. http://dx.doi.org/10.1029/2009JA015143

Hayakawa, M., Kasahara, Y., Nakamura, T., Hobara, Y., Rozhnoi, A., Solovieva, M., …, Korepanov, V. (2011a). Atmospheric gravity waves as a possible candidate for seismo-ionospheric perturbations. *J. Atmos. Electr., 31*(2), 129-140.

Hayakawa, M., Kawate, R., Molchanov, O. A., & Yumoto, K. (1996a). Result of ultra-low-frequency magnetic field measurements during the Guam earthquake of 8 August 1993. *Geophys. Res. Lett., 23*, 241-244. http://dx.doi.org/10.1029/95GL02863

Hayakawa, M., & Molchanov, O. A. (Eds.) (2002). *Seismo-Electromagnetics: Lithosphere-Atmosphere-Ionosphere Coupling.* p. 477. Tokyo, Japan: TERRAPUB.

Hayakawa, M., Molchanov, O. A., & NASDA/UEC team. (2004). Summary report of NASDA's earthquake remote sensing frontier project. *Phys. Chem. Earth, 29*, 617-625. http://dx.doi.org/10.1016/j.pce.2003.08.062

Hayakawa, M, Molchanov, O. A., Ondoh, T., & Kawai, E. (1996b). Anomalies in the sub-ionospheric VLF signals for the 1995 Hyogo-ken Nanbu earthquake. *J. Phys. Earth, 44*, 413-418. http://dx.doi.org/10.4294/jpe1952.44.413

Hayakawa, M., Ohta, K., Nickolaenko, A. P., & Ando, Y. (2005). Anomalous effect in Schumann resonance phenomena observed in Japan, possibly associated with the Chi-chi earthquake in Taiwan. *Ann. Geophysicae, 23*, 1335-1346. http://dx.doi.org/10.5194/angeo-23-1335-2005

Hayakawa, M., Ohta, K., Maekawa, S., Yamauchi, T., Ida, Y., Gotoh, T., …, Nakamura, T. (2006). Electromagnetic precursors to the 2004 Mid Niigata Prefecture earthquake. *Phys. Chem. Earth, 31*, 356-364. http://dx.doi.org/10.1016/j.pce.2006.02.023

Hayakawa, M., Rozhnoi, A., Solovieva, M., Hobara, Y., Ohta, K., Schekotov, A., & Fedorov E. (2013). The lower-ionospheric perturbation as a precursor to the 2011 March 11 Japan earthquake. *Geomatics, Natural Hazards and Risk*, 1-13.

Heincke, J., Koch, U., & Martinelli, G. (1995). CO_2 and radon measurements in the Vogtland area (Germany) - a contribution to earthquake prediction research. *Geophys. Res. Lett., 22*, 774-779.

Igarashi, G., Saeki, T., Takahata, N., Sano, Y., Sumikawa, K., Tasaka, S., Sasaki, Y., & Takahashi, M. (1995). Groundwater radon anomaly before the Kobe earthquake. *Science, 269*, 60-61. http://dx.doi.org/10.1126/science.269.5220.60

Kim, V. P., & Hegai, V. V. (1999). A possible presage of strong earthquakes in the night - time mid - latitude F2 region ionosphere. In M. Hayakawa (Ed.), *Atmospheric and Ionospheric Electromagnetic Phenomena Associated with Earthquakes* (pp. 619-627). Tokyo, Japan: TERRAPUB.

King, C. Y. (1986). Gas geochemistry applied to earthquake prediction: an overview. *J. Geophys. Res., 91*(B12), 12269-12281. http://dx.doi.org/10.1029/JB091iB12p12269

Klimenko, M. V., Klimenko, V. V., Zakharenkova, I. E., & Pulinets, S. A. (2012). Variations of equatorial electrojet as possible seismo-ionospheric precursor at the occurrence of TEC anomalies before strong earthquake. *Adv. Space Res., 49*, 509-517. http://dx.doi.org/10.1016/j.asr.2011.10.017

Klimenko, M. V., Klimenko, V. V., Zakharenkova, I. E., Pulinets, S. A., Zhao, B., & Tsidilina, M. N. (2011). Formation mechanism of great positive TEC disturbances prior to Wenchuan earthquake on May 12, 2008. *Adv. Space Res., 48*(3), 488-499. http://dx.doi.org/10.1016/j.asr.2011.03.040

Kondo, G. (1968). The variation of the atmospheric electric field at the time of earthquake. *Memoirs of the Kakioka Magnetic Observatory, 13*(1), 11-23.

Kopytenko, Yu. A., Matiashvili, T. G., Voronov, P. M., Kopytenko, E. A., & Molchanov, O. A. (1993). Detection of ultra-low-frequency emissions connected with the Spitak earthquake and its aftershock activity, based on geomagnetic pulsations data at Dusheti and Vardzia observatories. *Phys. Earth Planet. Inter., 77*, 85-95. http://dx.doi.org/10.1016/0031-9201(93)90035-8

Korepanov, V., Hayakawa, M., Yampolski, Y., & Lizunov, G. (2009). AGW as a seismo-ionospheric coupling responsible agent. *Phys. Chem. Earth, 34*(6-7). In M. Hayakawa, J. Y. Liu, K. Hattori, & L. Telesca (Eds.), Special issue, Electromagnetic Phenomena Associated with Earthquakes and Volcanoes, 485-495.

Kuo, C. L., Huba, J. D., Joyce, G., & Lee, L. C. (2011). Ionosphere plasma bubbles and density variations induced by pre-earthquake rock currents and associated surface charges. *J. Geophys. Res., 116*, A10317. http://dx.doi.org/10.1029/2011JA016628

Laptukhov, A. I., Sorokin, V. M., & Yaschenko, A. K. (2009). Disturbance of the ionosphere D region by electric current in the atmosphere–ionosphere electric circuit. *Geomagn. Aeron., 49*, 805-811. http://dx.doi.org/10.1134/S0016793209060103

Larkina, V. I., Migulin, V. V., Molchanov, O. A., Kharkov, I. P., Inchin A. S. & Schvetsova, V. B. (1989). Some statistical results on very low frequency radio wave emissions in the upper ionosphere over earthquake zones. *Phys. Earth Planet. Inter., 57*, 100-109. http://dx.doi.org/10.1016/0031-9201(89)90219-7

Liperovsky, V. A., Meister, C. V., Liperovskaya, E. V., & Bogdanov, V. V. (2008). On the generation of electric field and infrared radiation in aerosol clouds due to radon emanation in the atmosphere before earthquakes. *Natural Hazards Earth Syst. Sci., 8*, 1199-1205. http://dx.doi.org/10.5194/nhess-8-1199-2008

Liperovsky, V. A., Meister, C. V., Liperovskaya, E. V., Davidov, V. F., & Bogdanov, V. V. (2005). On the possible influence of radon and aerosol injection on the atmosphere and ionosphere before earthquakes. *Natural Hazards Earth Syst. Sci., 5*, 783-789. http://dx.doi.org/10.5194/nhess-5-783-2005

Liperovsky, V. A., Meister, C. V., Schlegel, K., & Haldoupis, Ch. (1997). Currents and turbulence in and near mid-latitude sporadic E-layers caused by strong acoustic impulses. *Ann. Geophys., 15*, 767-773.

Liperovsky, V. A., Pokhotelov, O. A., & Shalimov, S. L. (1992). *Ionospheric Earthquake Precursors*. p. 304. Moscow, Russia: Nauka.

Liu, J. Y. (2009). Earthquake precursors observed in the ionospheric F-region, In M. Hayakawa (Ed.), *Electromagnetic Phenomena Associated with Earthquakes* (pp. 187-204). Trivandrum, India: Transworld Research Network.

McGorman, D. R., & Rust, W. D. (1998). *The Electrical Nature of Storms*. Oxford, UK: Oxford Univ. Press.

Molchanov, O. A. (1993). Wave and plasma phenomena inside the ionosphere and the magnetosphere associated with earthquakes. In W. R. Stone (Ed.), *Review of Radio Science 1990-1992* (pp. 591-600). New York, USA: Oxford University Press.

Molchanov, O. A. (1999). Fracturing as an underlying mechanism of seismo-electric signals. In M. Hayakawa (Ed.), *Atmospheric and Ionospheric Electromagnetic Phenomena Associated with Earthquakes* (pp. 349-356). Tokyo, Japan: TERRAPUB.

Molchanov, O. A. (2009). Lithosphere-atmosphere-ionosphere coupling due to seismicity. In M. Hayakawa (Ed.), *Electromagnetic Phenomena Associated with Earthquakes* (pp. 255-279). Trivandrum, India: Transworld Research Network.

Molchanov, O. A., & Hayakawa, M. (1995). Generation of ULF electromagnetic emissions by microfracturing. *Geophys. Res. Lett., 22*, 3091-3094. http://dx.doi.org/10.1029/95GL00781

Molchanov, O. A., & Hayakawa, M. (1996). VLF transmitter earthquake precursors influenced by a change in atmospheric electric field. *Proc. 10th International Conference on Atmospheric Electricity*, June 10-14, Osaka, Japan, 428-431.

Molchanov, O. A., & Hayakawa, M. (1998). Subionospheric VLF signal perturbations possibly related to earthquakes. *J. Geophys. Res., 103*, 17489-17504. http://dx.doi.org/10.1029/98JA00999

Molchanov, O. A., & Hayakawa, M. (2008). *Seismo Electromagnetics and Related Phenomena: History and latest results*. p. 189. Tokyo, Japan: TERRAPUB.

Molchanov, O. A., Kopytenko, Yu. A., Voronov, P. M., Kopytenko, E. A., Matiashvili, T. G., Fraser-Smith, A. C., & Bernardy, A. (1992). Results of ULF magnetic field measurements near the epicenters of the Spitak (Ms=6.9) and Loma Prieta (Ms=7.1) earthquakes: Comparative analysis. *Geophys. Res. Lett., 19*, 1495-1498. http://dx.doi.org/10.1029/92GL01152

Molchanov, O. A., Mazhaeva, O. A., Golyavin, A. N., & Hayakawa, M. (1993). Observation by Intercosmos-24 satellite of ELF-VLF electromagnetic emissions associated with earthquakes. *Ann. Geophys., 11*, 431-440.

Molchanov, O. A., Hayakawa, M., & Rafalsky, V. A. (1995). Penetration characteristics of electromagnetic emissions from an uderground seismic source into the atmosphere, ionosphere, and magnetosphere. *J. Geophys. Res., 100*, 1691-1712. http://dx.doi.org/10.1029/94JA02524

Molchanov, O. A., Fedorov, E., Schekotov, A., Gordeev, E., Chebrov, V., Surkov, V., …, Biagi P. F. (2004). Lithosphere-atmosphere-ionosphere coupling as governing mechanism for preseismic short-term events in atmosphere and ionosphere. *Natural Hazards Earth Syst. Sci., 4*, 757-767. http://dx.doi.org/10.5194/nhess-4-757-2004

Namgaladze, A. A., Klimenko, M. V., Klimenko, V. V., & Zakharenkova, I. E., (2009). Physical mechanism and mathematical simulation of ionosphere earthquakeprecursors observed in total electron content. *Geomagn. Aeron., 49*, 252-262. http://dx.doi.org/10.1134/S0016793209020169

Nikiforova, N. N., & Michnowski, S. (1995). Atmospheric electric field anomalies analysis during great Carpatian Earthquake at Polish Observatory Swider. *IUGG XXI General Assembly Abstr.*, Boulder, Colo.: VA11D-16.

Omori, Y., Nagahama, H., Kawada, Y., Yasuoka, Y., Ishikawa, T., Tokonami, S., & Shinogi M. (2008). Preseismic alteration of atmospheric electrical conditions due to anomalous radon emanation. *Phys. Chem. Earth, 33*, 276-284.

Omori, Y., Yasuoka, Y., Nagahama, H., Kawada, Y., Ishikawa, T., Tokonami, S., & Shinagi, M. (2007). Anomalous radon emanation linked to preseismic electromagnetic phenomena. *Natural Hzards Earth Syst. Sci., 7*, 629-635. http://dx.doi.org/10.5194/nhess-7-629-2007

Ouzounov, D., Pulinets, S., Hattori, K., Kafatos, M., & Taylor, P. (2012). Atmospheric signals associated with major earthquakes: A multi-sensor approach. In M. Hayakawa (Ed.), *The Frontier of Earthquake Prediction Studies* (pp. 510-531). Tokyo, Japan: Nihon-senmontosho-Shuppan.

Park, C. G., & Dejnakarintra, M. (1973). Penetration of thundercloud electric fields into the ionosphere and magnetosphere. 1. Middle and auroral latitudes. *J. Geophys. Res., 84*, 960-964. http://dx.doi.org/10.1029/JA084iA03p00960

Parrot, M. (1994). Statistical study of ELF/VLF emissions recorded by low-latitude satellite during seismic events. *J. Geophys.Res., 99*(23), 339-347.

Parrot, M. (2009). Anomalous seismic phenomena: View from space, In M. Hayakawa (Ed.), *Electromagnetic Phenomena Associated with Earthquakes* (pp. 205-233). Trivandrum, India: Transworld Research Network.

Parrot, M. (2011). Statistical analysis of the ion density measured by the satellite DEMETER in relation with the seismic activity. *Earthquake Sci., 24*, 513-548. http://dx.doi.org/10.1007/s11589-011-0813-3

Parrot, M., & Lefeuvre, F. (1985). Correlation between GEOS VLF emissions and earthquakes. *Ann. Geophysicae, 3*, 737-748.

Pilipenko, V. A., Fedorov, E. N., Yagova, N. V., & Yumoto, K. (1999). Attempt to detect ULF electro - magnetic activity preceding earthquake. In M. Hayakawa (Ed.), *Atmospheric and Ionospheric Electromagnetic Phenomena Associated with Earthquakes* (pp. 203-214). Tokyo, Japan: Terra Scientific Publishing Company (TERRAPUB).

Pulinets, S. A. (2009a). Lithosphere-atmosphere-ionosphere coupling (LAIC) model, In M. Hayakawa (Ed.), *Electromagnetic Phenomena Associated with Earthquakes* (pp. 235-253). Trivandrum, India: Transworld Research Network.

Pulinets, S. A. (2009b). Physical mechanism of the vertical electric field generation over active tectonic faults. *Adv. Space Res., 44*, 767-773. http://dx.doi.org/10.1016/j.asr.2009.04.038

Pulinets, S. A., Alekseev, V. A., Legenka, A. D., & Khegai, V. V. (1997). Radon and metallic aerosols emanation before strong earthquakes and their role in atmosphere and ionosphere modification. *Adv. Space Res., 20*, 2173-2176. http://dx.doi.org/10.1016/S0273-1177(97)00666-2

Pulinets, S. A., & Boyarchuk, K. A. (2004). *Ionospheric Precursors of Earthquakes.* p. 315. Berlin, Germany: Springer.

Pulinets, S. A., Boyarchuk, K. A., Hegai, V. V., Kim, V. P., & Lomonosov, A. M. (2000). Quasielectrostatical model of atmosphere-thermosphere-ionosphere coupling. *Adv. Space Res., 26*, 1209-1218. http://dx.doi.org/10.1016/S0273-1177(99)01223-5

Pulinets, S. A., Legen'ka, A. D., & Alekseev, V. A. (1994). Pre-earthquake ionospheric effects and their possible mechanisms. In H. Kikuchi (Ed.), *Dusty and Dirty Plasmas, Noise, and Chaos in Space and in the Laboratory* (pp. 545-557). New York, NY: Plenum Press. http://dx.doi.org/10.1007/978-1-4615-1829-7_46

Pulinets, S. A., Legen'ka, A. D., Gaivoronskaya, T. V., & Depuev, V. Kh. (2003). Main phenomenological features of ionospheric precursors of strong earthquakes. *J. Atmos. Solar-Terr. Phys*., 65, 1337-1347. http://dx.doi.org/10.1016/j.jastp.2003.07.011

Pulinets, S. A., & Ouzounov, D. (2011). Lithosphere-Atmosphere-Ionosphere Coupling (LAIC) model-An unified concept for earthquake precursors validation. *J. Asian Earth Sci., 41*, 371-382. http://dx.doi.org/10.1016/j.jseaes.2010.03.005

Qiang, Z. J., Dian, C. G., & Li, L. Z. (1999). Satellite thermal infrared precursors of two moderate - strong earthquakes in Japan and impending earthquake prediction. In M. Hayakawa (Ed.), *Atmospheric and Ionospheric Electromagnetic Phenomena Associated with Earthquakes* (pp. 747-745). Tokyo, Japan: Terra Scientific Publishing Company (TERRAPUB).

Rakov, V. A., & Uman, M. A. (2002). *Lightning: Physics and Effects.* Cambridge, UK: Cambrdige Univ. Press.

Rapoport, Y., Grimalsky, V., Hayakawa, M., Ivchenko, V., Juarez-R, D., Koshevaya, S., & Gotynyan, O. (2004). Change of ionospheric plasma parameters under the influence of electric field which has lithospheric origin and due to radon emanation. *Phys. Chem. Earth, 29*, 579-587. http://dx.doi.org/10.1016/j.pce.2003.09.018

Rozhnoi, A., Solovieva, M., Molchanov, O. A., & Hayakawa, M. (2004). Middle latitude LF(40kHz) phase variations associated with earthquakes for quiet and disturbed geomagnetic conditions. *Phys. Chem. Earth, 29*, 589-598. http://dx.doi.org/10.1016/j.pce.2003.08.061

Rozhnoi, A. A., Solovieva, M. S., Molchanov, O. A., Hayakawa, M., Maekawa, S., & Biagi, P. F. (2005). Anomalies of LF signal during seismic activity in November–December 2004. *Natural Hazards Earth Syst. Sci., 5*, 657-660. http://dx.doi.org/10.5194/nhess-5-657-2005

Rulenko, O. P. (2000). Operative precursors of earthquakes in the near-ground atmosphere electricity. *Volcanology and Seismology, 4*, 57-68.

Ruzhin, Y., Nomicos, C., & Vallianatos, F. (2000). High frequency seismoprecursor emissions. *Proc. 15th Wroclaw EMC Symposium*, 512-517.

Ruzhin, Yu., & Nomicos, C. (2007). Radio VHF precursors of earthquakes. *Natural Hazards, 40*, 573-583. http://dx.doi.org/10.1007/s11069-006-9021-1

Rycroft, M. J., Israelsson, S., & Price, C. (2000). The global atmospheric electric circuit, solar activity and climate change. *J. Atmos. Solar-Terr. Phys., 62*, 1563-1576. http://dx.doi.org/10.1016/S1364-6826(00)00112-7

Sapkota, B. K., & Varshneya, N. C. (1990). On the global atmospheric electrical circuit. *J. Atmos. Terr. Phys., 52*, 1 -20. http://dx.doi.org/10.1016/0021-9169(90)90110-9

Schekotov, A., Molchanov, O. A., Hattori, K., Fedorov, E., Gladyshev, V. A., Belyaev, G. G., …, Hayakawa, M. (2006). Seismo-ionospheric depression of the ULF geomagnetic fluctuations at Kamchatka and Japan. *Phys. Chem. Earth, 31*, 313-318. http://dx.doi.org/10.1016/j.pce.2006.02.043

Sorokin, V. M. (2007). Plasma and Electromagnetic Effects in the Ionosphere Related to the Dynamics of Charged Aerosols in the Lower Atmosphere. *Russian J. Physical Chemistry B, 1*(2), 138-170.

Sorokin, V. M., & Chmyrev, V. M. (1999). Modification of the ionosphere by seismic related electric field. In M. Hayakawa (Ed.), *Atmospheric and Ionospheric Electromagnetic Phenomena Associated with Earthquakes* (pp. 805 - 818). Tokyo, Japan: Terra Scientific Publishing Company (TERRAPUB).

Sorokin, V. M., & Chmyrev, V. M. (2010). Atmosphere-ionosphere electrodynamic coupling. In V. L. Bychkov et al. (Eds.), *The Atmosphere and Ionosphere: Dynamics, Processes and Monitoring* (pp. 97-146). Berlin, Germany: Springer. http://dx.doi.org/10.1007/978-90-481-3212-6_3

Sorokin, V. M., Chmyrev, V. M., & Hayakawa, M. (2000). The Formation of ionosphere - magnetosphere ducts over the seismic zone. *Planet. Space Sci., 48*, 175-180. http://dx.doi.org/10.1016/S0032-0633(99)00096-3

Sorokin, V. M., Chmyrev, V. M., & Isaev, N. V. (1998). A generation model of mall-scale geomagnetic field-aligned plasma inhomogeneities in the ionosphere. *J. Atmos. Solar-Terr. Phys., 60*, 1331-342. http://dx.doi.org/10.1016/S1364-6826(98)00078-9

Sorokin, V. M., Chmyrev, V. M., & Yaschenko, A. K. (2001). Electrodynamic model of the lower atmosphere and the ionosphere coupling. *J. Atmos. Solar-Terr. Phys., 63*, 1681-1691. http://dx.doi.org/10.1016/S1364-6826(01)00047-5

Sorokin, V. M., Chmyrev, V. M., & Yaschenko, A. K. (2003). Ionospheric generation mechanism of geomagnetic pulsations observed on the Earth's surface before earthquake. *J. Atmos. Solar-Terr. Phys., 64*, 21-29. http://dx.doi.org/10.1016/S1364-6826(02)00082-2

Sorokin, V. M., Chmyrev, V. M., & Yaschenko, A. K. (2005a). Theoretical model of DC electric field formation in the ionosphere stimulated by seismic activity. *J. Atmos. Solar-Terr. Phys*., 67, 1259-1268. http://dx.doi.org/10.1016/j.jastp.2005.07.013

Sorokin, V. M., Chmyrev, V. M., & Yaschenko, A. K. (2006a). Possible DC electric field in the ionosphere related to seismicity. *Adv. Space Res., 37*, 666-670. http://dx.doi.org/10.1016/j.asr.2005.05.066

Sorokin, V. M., Fedorov, E. N., Schekotov, A. Yu., Molchanov, O. A., & Hayakawa, M. (2004). Depression of the ULF geomagnetic pulsation related to ionospheric irregularities. *Ann. Geophysics, 47*, 191-198.

Sorokin, V. M., & Hayakawa, M. (2008). On the generation of narrow-banded ULF/ELF pulsations in the lower ionospheric conducting layer. *J. Geophys. Res., 113*, a06306. http://dx.doi.org/10.1029/2008JA013094

Sorokin, V. M., & Pokhotelov, O. A. (2010). Generation of ULF geomagnetic pulsations during early stage of earthquake preparation. *J. Atmos. Solar -Terr. Phys., 72*, 763-766. http://dx.doi.org/10.1016/j.jastp.2010.03.021

Sorokin, V. M., Ruzhin, Yu. Ya., Kuznetsov, V. D., & Yaschenko, A. K. (2012a). Model of electric discharges formation in the lower atmosphere over a seismic region. *Geomatics, Natural Hazards and Risk, 3*, 225-238. http://dx.doi.org/10.1080/19475705.2011.604799

Sorokin, V. M., Ruzhin, Yu. Ya., Yaschenko, A. K., & Hayakawa, M. (2011a). Generation of VHF radio emissions by electric discharges in the lower atmosphere over a seismic region. *J. Atmos. Solar-Terr. Phys., 73*, 664-670. http://dx.doi.org/10.1016/j.jastp.2011.01.016

Sorokin, V. M., Ruzhin, Yu. Ya., Yaschenko, A. K., & Hayakawa, M. (2012b). Seismic - related electric discharges in the lower atmosphere. In M. Hayakawa (Ed.), *The Frontier of Earthquake Prediction Studies* (pp. 592-611). Tokyo, Japan: Nihon-senmontosho-Shuppan.

Sorokin, V. M., Sergeev, I. Yu., & Pokhotelov, O. A. (2009). Low latitude gyrotropic waves in a finite thickness ionospheric conducting layer. *J. Atmos. Solar-Terr. Phys., 71*, 175-179. http://dx.doi.org/10.1016/j.jastp.2008.10.001

Sorokin, V. M., Yaschenko, A. K., Chmyrev, V. M., & Hayakawa, M. (2005b). DC electric field amplification in the mid-latitude ionosphere over seismically active faults. *Natural Hazards Earth Syst. Sci., 5*, 661-666. http://dx.doi.org/10.5194/nhess-5-661-2005

Sorokin, V. M., Yaschenko, A. K., & Hayakawa, M. (2006b). Formation mechanism of the lower ionosphere disturbances by the atmosphere electric current over a seismic region. *J. Atmos. Solar-Terr. Phys., 68*(11), 1260-1268. http://dx.doi.org/10.1016/j.jastp.2006.03.005

Sorokin, V. M., Yaschenko, A. K., & Hayakawa, M. (2007). A perturbation of DC electric field caused by light ion adhesion to aerosols during the growth in seismic-related atmospheric radioactivity. *Natural Hazards Earth Syst. Sci., 7*, 155-163. http://dx.doi.org/10.5194/nhess-7-155-2007

Sorokin, V. M., & Yaschenko, A. K. (2000). Electric field disturbance in the earth-ionosphere layer. *Adv. Space Res., 26*(8), 1219-1223. http://dx.doi.org/10.1016/S0273-1177(99)01221-1

Surkov, V., & Pilipenko, V. (1999). The physics of pre-seismic electromagnetic ULF signals. In M. Hayakawa (Ed.), *Atmospheric and Ionospheric Electromagnetic Phenomena Associated with Earthquakes* (pp. 357-370). Tokyo, Japan: Terra Scientific Publishing Company (TERRAPUB).

Tronin, A. A. (1999). Satellite thermal survey application for earthquake prediction. In M. Hayakawa (Ed.), *Atmospheric and Ionospheric Electromagnetic Phenomena Associated with Earthquakes* (pp. 717-746). Tokyo, Japan: Terra Scientific Publishing Company (TERRAPUB).

Tronin, A. A. (2006). Remote sensing and earthquakes: A review. *Phys. Chem. Earth, 31*, 138-142. http://dx.doi.org/10.1016/j.pce.2006.02.024

Tronin, A. A., Hayakawa, M., & Molchanov, O. A. (2002). Thermal IR satellite data application for earthquake research in Japan and China. *J. Geodynamics, 33*, 519-534. http://dx.doi.org/10.1016/S0264-3707(02)00013-3

Uyeda, S., Nagao, T., & Kamogawa, M. (2009). Short-term earthquake prediction: current state of seismo-electromagnetics, *Tectonophys., 470*, 205-213. http://dx.doi.org/10.1016/j.tecto.2008.07.019

Vallianatos, F., & Nomicos, K. (1998). Seismogenic radioemissions as earthquake precursors in Greece. *Phys. Chem. Earth, 23*(9-10), 953-957. http://dx.doi.org/10.1016/S0079-1946(98)00126-8

Varotsos, P. (2001). A review and analysis of electromagnetic precursory phenomena. *Acta Geophysica Polonica, 49*(1), 1-42.

Vershinin, E. F., Buzevich, A. V., Yumoto, K., Saita, K., & Tanaka, Y. (1999). Correlations of seismic activity with electromagnetic emissions and variations in Kamchatka region. In M. Hayakawa (Ed.), *Atmospheric and Ionospheric Electromagnetic Phenomena Associated with Earthquakes* (pp. 513-517). Tokyo, Japan: Terra Scientific Publishing Company (TERRAPUB).

Virk, H. S., & Singh, B. (1994). Radon recording of Uttarkashi earthquake. *Geophys. Res. Lett., 21*, 737-741. http://dx.doi.org/10.1029/94GL00310

Voitov, G. I., & Dobrovolsky, I. P. (1994). Chemical and isotope - carbonic instability of the soil gases in the seismic regions. *Izvestiya AN SSSR, Fizika Zemli, 3*, 20-27.

Yasuda, Y., Ida, Y., Goto, T., & Hayakawa, M. (2009). Interferometric direction finding of over-horizon VHF transmitter signals and natural VHF radio emissions possibly associated with earthquakes. *Radio Sci., 44*, RS2009. http://dx.doi.org/10.1029/2008RS003884

Yasuoka, Y., Igarashi, G., Ishikawa, T., Tokonami, S., & Shinogi, M. (2006). Evidence of precursor phenomena in the Kobe earthquake obtained from atmospheric radon concentration. *Appl. Geochem., 21*, 1064-1072. http://dx.doi.org/10.1016/j.apgeochem.2006.02.019

Yasuoka, Y., Ishikawa, T., Nagahama, H., Kawada, Y., Omori, Y., Tokonami, S., & Shinogi, M. (2012). Radon anomalies prior to earthquakes. In M. Hayakawa (Ed.), *The Frontier of Earthquake Prediction Studies* (pp. 410-427). Tokyo, Japan: Nihon-senmontosho-Shuppan.

Yonaiguchi, N., Ida, Y., Hayakawa, M., & Masuda, S. (2007a). A comparison of different fractal analyses for VHF electromagnetic emissions and their self-organization for the off-sea Miyagi-prefecture earthquake. *Natural Hazards Earth System Sci., 7*, 485-493. http://dx.doi.org/10.5194/nhess-7-485-2007

Yonaiguchi, N., Ida, Y., Hayakawa, M., & Masuda, S. (2007b). Fractal analysis for VHF electromagnetic noises and the identification of preseismic signature of an earthquake. *J. Atmos. Solar-terr. Phys., 69*, 1825-1832. http://dx.doi.org/10.1016/j.jastp.2007.08.002

Zakharenkova, I. E., Shagimuratov, I. I., Tepenitzina, N. Yu., & Krankowski, A. (2008). Anomalous modification of the ionospheric Total Electron Content prior to the 26 September 2005 Peru earthquake. *J. Atmos. Solar-Terr. Phys., 70*, 1919-1928. http://dx.doi.org/10.1016/j.jastp.2008.06.003

Zolotov, O. V., Namgaladze, A. A., Zakharenkova, I. E., Shagimuratov, I. I., & Martynenko, O. V. (2008). Simulations of the equatorial ionosphere to the seismic electric field sources. *Proc. 7th International Conference "Problems of Geocosmos",* St. Petersburg, Russia: 26-30 May 2008, 492-496.