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Plasma and Electromagnetic Effects Caused by the Seismic-Related Disturbances of Electric Current in the Global Circuit

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Abstract

This paper is devoted to the use of an electrodynamical model for lithosphere – atmosphere – ionosphere (LAI) coupling to explain plasma and electromagnetic earthquake (EQ) precursors. Our consideration is based on the calculation results of electromagnetic perturbations and ionospheric irregularities accompanying the electric field and electric current occurring in the global atmosphere – ionosphere electric circuit. Our theoretical results are confirmed by satellite- and ground-based experimental data of plasma and electromagnetic perturbations obtained for several days before an EQ. It is shown that the growth of current in the global circuit might result in the AGW (acoustic gravity wave) instability in the ionosphere, the formation of field-aligned current and plasma irregularities, magnetic field ULF oscillations and electromagnetic ELF radiation, spectral broadening of VLF transmitter signals registered by satellites, depressions of ULF magnetic pulsations, VHF radio emissions generated in the troposphere and propagation of the signals of a VHF transmitter behind the horizon. Moreover, the generation of electric current in the global circuit is accompanied with the modification of D, E and F ionospheric layers. All of these phenomena are shown to be attributed just to a single cause; namely, the variation of conducting electric current in the global circuit by the injection of charged aerosols into the atmosphere during seismic activity.

Keywords: earthquakes, ionospheric irregularities, lower ionosphere modification, over-the-horizon VHF propagation, random discharges radiation, TEC perturbation, ULF/ELF electromagnetic emissions

1. Introduction

Satellite- and ground-based data suggest the relationship of lithospheric processes with electromagnetic and plasma disturbances within the ionosphere. Observational results of preseismic phenomena were discussed in many reviews (Gokhberg et al., 1988; Liperovsky et al., 1992; Molchanov, 1993; Buchachenko et al., 1996; Varotsos, 2001; Hayakawa & Molchanov, 2002; Pulinets & Boyarchuk, 2004; Molchanov & Hayakawa, 2008; Parrot, 2013). In order to understand the numerous ionospheric and electromagnetic earthquake (EQ) precursors, it is necessary to investigate their physical processes and to construct some models of seismicity effect on the ionospheric plasma. It is considered currently that this effect is mainly implemented either by acoustic gravity waves (AGWs) or electric field. The former possible influence of AGWs to the ionosphere during EQ preparation has been discussed in Mareev et al. (2002), Molchanov et al. (2004), Korepanov et al. (2009), and Hayakawa et al. (2011a). They considered both the sources of AGW generation and the processes accompanying the propagation of these waves into the ionosphere. Essentially another physical idea of the latter is used in the electrodynamical model of plasma and electromagnetic disturbances accompanying the EQ preparation, which has been discussed in the reviews by Sorokin (2007), Sorokin and Chmyrev (2010), and Sorokin and Hayakawa (2013). First this model allows us to account for the results of observation of quasi-static electric field both in the ionosphere and on the Earth's surface that cannot be explained by other models. In this electrodynamical model we find a mechanism in which there increases with altitude of the conducting electric current flowing in the Earth – ionosphere layer and a limitation of electric field on the Earth's surface. Calculations show that the value of electric field can attain the order of 10 mV/m in the ionosphere, but, at the same time, it does not exceed the background value on the Earth's surface. This field stimulates the development of plasma and electromagnetic disturbances which will be considered below. The present work is the second part of our review, the first part of which was already published in Sorokin and Hayakawa (2013). First part of our review is devoted to the nature of quasi-static electric field occurring in the ionosphere during EQ preparation. Below, in the second part of our review, we consider the formation of plasma and electromagnetic disturbances accompanying the growth of electric field and the interpretation of observed phenomena.

2. Small-Scale Ionospheric Irregularities

2.1 Formation of Irregularities by AGW Instability in the Electric Field

The growth of electric field in the ionosphere leads to an instability of AGWs (Sorokin et al., 1998; Sorokin & Chmyrev, 1999a). The origin of this instability is related with transformations of heating emitted by the ionospheric current into the wave energy. Propagation of AGWs in this case results in the perturbation of conductivity and electric current, and on certain conditions the heating emitted by the electric current leads to a growth of AGW amplitude. The energy source of this instability is an EMF (electromotive force) of ambient electric field. The energy of this field is transferred to the wave energy, and its value grows with the electric field. The value of critical field is defined by an equality of the heating energy amount of disturbed current and the energy amount dissipating by magnetic viscosity. For the field less than the critical value, the initial disturbance damps, while for the field greater than the critical one the wave builds up. Our estimation shows that the value of critical field is (6~10)mV/m. Figure 1 depicts a calculation result of the frequency dependence of the refractive index $n(\omega)$ and absorption coefficient $\kappa(\omega)$. The figure shows that in the vicinity of Brunt-Väisälä frequency ω_g the refractive index increase in several times and the absorption coefficient is negative, attaining a minimal value, so that the amplitude of waves with frequency ω_g is exponentially enhanced. These waves are superimposed over the background, forming a periodical structure with spatial scale $l=\pi a/\omega_g\, n(\omega_g)$ (a: sound velocity). The refractive index attains a maximum value $n(\omega_g)$, which leads to a significant reduction of wave phase velocity $v_g=a/n(\omega_g)<a$ in comparison to the sound velocity a. Exponential growth of the AGW amplitude in the electric field in the ionosphere is limited by vortex formation, and this nonlinear stage of development of wave instability was extensively considered by Chmyrev and Sorokin (2010). The nonlinear equation for low-frequency branch of AGWs has been derived, which is a stationary solution of the equation in nonlinear stage of wave propagation with constant velocity. The current function derived shows that the instability in the electric field transforms AGWs in the dipole vortex. For the electric field greater than the threshold value, there are generated the dipole vortex structures in the ionosphere.

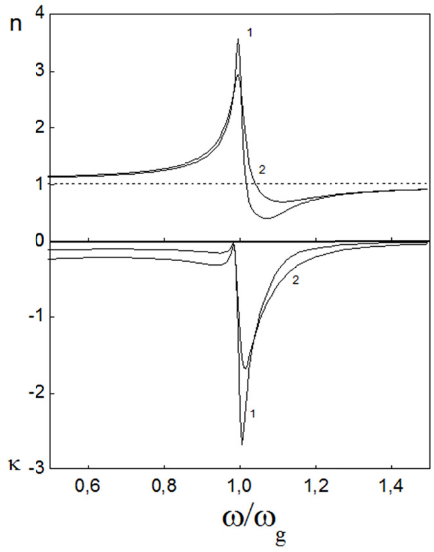

Figure 1. The frequency dependence of the refraction index and absorption coefficient of acoustic-gravity waves in the ionosphere in the presence of an external electric field

The curve 1 corresponds to the case of $\alpha=0.2$ and the curve 2, to the case of $\alpha=1$, where α is the variation of ions density relative to that of molecular density in the wave (Sorokin et al., 1998).

The perturbation of plasma in a vortex changes simultaneously the conductivity inside the vortex that results in the formation of horizontal irregularities of conductivity in the lower ionosphere. Their appearance is accompanied with the formation of plasma irregularities elongated along the magnetic field in the upper ionosphere (Sorokin et al., 1998, 2000), and such irregularities of conductivity change the ionospheric electric fields. High conductivity along magnetic field lines results in the electric field propagation to the upper ionosphere and the magnetosphere. The fields are transferred by the field-aligned currents which are closed by the transverse currents in the ionosphere due to Pedersen conductivity. Since the field-aligned currents are carried by electrons while the transverse currents are carried by ions, the upward propagation of the transverse electric field is followed by the local variations of plasma density. This means that the excitation of horizontal spatial structure of conductivity in the lower ionosphere may result in the formation of plasma layers elongated along the geomagnetic field. Transverse spatial scale of the layers coincides with the scale of conductivity irregularities. Sorokin et al. (1998) made an estimation of the relative changes of plasma density in the layer elongated along the magnetic field $\Delta N/N_0 \approx (1.6\sim16)$ % and of the transverse spatial scale of irregularities $l \approx$ 4~40 km. Figure 2 depicts a schematic illustration and an example of satellite registration of plasma density fluctuations and ULF (ultra low frequency) oscillations of geomagnetic field. When a satellite crosses the field-aligned currents and related field-aligned plasma irregularities with velocity 8 km/s the oscillations of plasma density and ULF oscillations of geomagnetic field with amplitude $b \approx 5$nT are registered with period $\Delta t \approx$ (0.4~4) s. The theoretical researches implemented allow us to formulate the mechanism of horizontal irregularities in the lower ionosphere and plasma layers elongated along the magnetic field. These irregularities are excited when the electric field exceeds the critical value (5-10) mV/m.

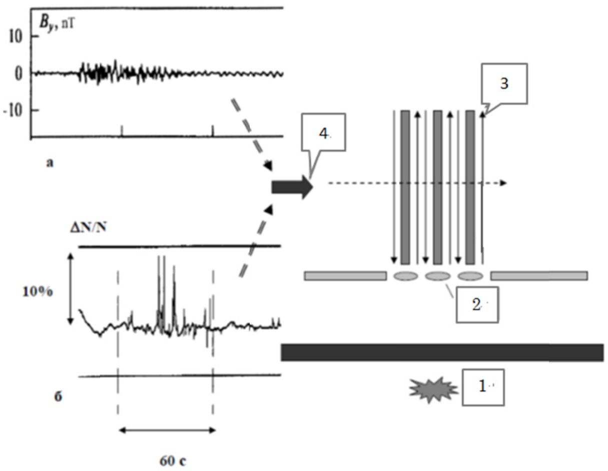

Figure 2. Schema and examples of satellite observations of ULF magnetic field oscillations, electron number density fluctuations and ELF electromagnetic emissions caused by the formation of ionosphere conductivity irregularities (Chmyrev et al., 1989, 1997)

1. Earthquake. 2. Irregularities of the ionosphere conductivity. 3. Field-aligned currents and irregularities of electron number density. 4. Satellite trajectory crossing the disturbed region.

It is necessary to note that the development of AGW instability in the ionosphere leading to the formation of significant spatial gradients of plasma density and allocated structure of field-aligned currents at certain gradient values causes the splitting of current layers ≈ and generation of filamentary structures with characteristic size across the magnetic field of the order of 100 m in the upper ionosphere (Chmyrev et al., 2008). The importance of these effects in applications to EQ- related ionospheric disturbances was first noted by Chmyrev et al. (1999). Chmyrev et al. (1988) also demonstrated the effects of plasma and field-aligned current filamentation due to strong plasma density gradients in the high-latitude ionosphere. Streltsov et al. (1990) have shown that the parallel current sheets or the solitary current disturbances in the auroral plasma generate the vortex chains. Thus, our calculations made in this section indicate that one can expect two characteristic spatial scales for seismic-related ionospheric disturbances: 4-40 km and ~100 m across the magnetic field.

The plasma and electromagnetic effects connected with AGW instabilities and the formation of small-scale irregularities are confirmed by numerous satellite- and ground-based observations in seismic regions. Further analyses of satellite data revealed the electric field disturbances up to 15 mV/m in the ionosphere over a typhoon region (Isaev et al., 2002; Sorokin et al., 2005). Generation of such fields is accompanied by the local growth of plasma density and formation of magnetic field-aligned plasma layers with transverse scales 10-20 km and 20-40 km. In the records observed onboard the satellite crossing these layers they are seen as plasma density fluctuations, and similar results are repeated for dozens of events. The argument for the formation of field-aligned currents in the ionosphere resulting in the formation of plasma irregularity can be found in the satellite data presented by Chmyrev et al. (1989). Figure 2 shows such an example of the variations of two horizontal magnetic field components in the frequency range of 0.1-8 Hz along with the vertical component of quasi-static electric field which were observed onboard the IB-1300 satellite within a 15-min interval before the EQ occurred on January 12, 1982 at 17.50.26 UT. The quasi-static electric field 3-7 mV/m was observed in two specific zones: above the EQ focus and in its magnetically conjugate region, and the corresponding size was (1°-1.5°) in latitude. The amplitude of geomagnetic pulsations at the frequency about 1 Hz observed in these regions was ~ 3 nT. The physical model presented above predicts a growth of the electric field in the ionosphere above the zone of a developing EQ and then the AGW dissipative instability. As a result the horizontal irregularities of ionospheric conductivity are formed and there arise field-aligned currents. The small-scale (4-10km) fluctuations of plasma density $dN_e/N_e \approx 3\text{-}8$ % correlated with the increase in seismic-related ELF (extremely low frequency) emission intensity were registered (Chmyrev et al., 1997), and the sizes of disturbed zones of plasma density dN_e and ELF waves occupy a latitude range (3°-4.5°). An analysis of COSMOS-1809 satellite data on ELF emissions shows that electromagnetic waves at the frequencies 140-450 Hz were regularly observed in the ionosphere over the region of enhanced aftershock activity independently of geophysical conditions. This result was primarily obtained by Serebryakova et al. (1992) on the basis of analyses of the first three events from COSMOS - 1809 and of the data of AUREOL -3 satellites. Chmyrev et al. (1997) confirmed this result by two other events. The new result of this study is that the small-scale plasma irregularities $dN_e/N_e \sim 3\text{-}8$ % with characteristic scales 4-10 km along the orbit have been revealed in geomagnetic field tubes connected with the EQ epicenter region, in which seismic-related ELF (extremely low frequency) emissions were detected simultaneously. These results are confirmed by recent satellite DEMETER data (Akhoondzadeh, 2013), which revealed ULF oscillations of magnetic field (1-3) days before an EQ on 29.09.2009 in the vicinity of Samoa. Electromagnetic perturbations in magnetic tubes connected with the EQ epicenter are observed during several days before the event. Similar ULF/ELF electromagnetic field and plasma perturbation were registered by satellite DEMETER during an EQ with magnitude M>6.0 in Chili (Zhang et al., 2011).

2.2 VLF/ELF Electromagnetic Effects

These irregularities can play a role of whistler ducts (Sorokin et al., 2000). The estimated transverse size of ducts and their separation are ~10 km, and the relative plasma density enhancement within the duct is of the order of a few percent. So we studied the principal possibility of duct formation and modification of whistler propagation characteristics under the influence of seismic-related disturbances of DC electric field in the lower ionosphere. The model predicts the following effects which could be identified in the experimental data:

1) The movement of plasma irregularities (ducts) in the horizontal direction with the velocity less than or of the order of the velocity of sound in the *E* layer;
2) The multi-ray (fine) structure of whistlers associated with the structure of the distribution of plasma irregularities excited by AGW;
3) The correlation of anomalous whistlers with the enhancement of DC electric field and plasma density oscillations as well as with the formation of field-aligned electric currents and associated transverse magnetic field disturbances (ULF magnetic pulsations).

Hayakawa et al. (1993) studied the possible influence of seismic activity on the propagation of magnetospheric whistlers at low latitudes. Using the whistler data observed at Sugadaira in Japan, they have found that a drastic change in the characteristics of low-latitude whistlers is observed prior to an EQ, in such a way that the anomalous whistlers with dispersions greater than twice the typical value, exhibit a substantial increase in occurrence during seismic activity. This suggests the generation of well-defined whistler ducts before and after the seismic activity.

The effects of small-scale plasma density irregularities in the ionosphere over the seismic zone on the characteristics of VLF (very low frequency) transmitter signals propagated through these disturbances and then registered onboard a satellite, have been investigated by Chmyrev et al. (2008), and their main effect consists in observable spectral broadening of VLF signals. The calculations have given spatial scales of plasma density irregularities across the magnetic field of the order of or less than 100 m. These size irregularities produce a noticeable effect on VLF signal spectral broadening, which is most pronounced in the case when the transmitter frequency is above, but close to the local LHR (lower hybrid resonance) frequency in the region where there are present small scale irregularities, which sets the requirement that the VLF transmitter frequency be in the range from 10 to 20 kHz. This corresponds to the operational band of most VLF transmitters. For the 100m irregularities we get the spectral broadening ~100 Hz that can easily be registered by a simple VLF receiver onboard satellites, provided that the VLF transmitter power is high enough. This effect together with the direct satellite measurements of plasma density variations can be used as an effective tool for diagnostics of seismic-related ionospheric disturbances and therefore considered as a possible ionospheric precursor to an EQ.

According to a mechanism of electromagnetic ELF precursors to EQs (Borisov et al., 1999), there arises the enhanced ELF emission in the upper ionosphere when pulsed electromagnetic radiation from lightning discharges propagating in the Earth-ionosphere waveguide is scattered by lower ionospheric conductivity inhomogeneities over an EQ region. Figure 3 illustrates a schematic illustration and an example of ELF radiation in the upper ionosphere, and intensities of lightning induced whistler mode waves in the upper ionosphere vary substantially depending on lightning activity. The modeling yields the maximum of magnetic field amplitude of ELF emissions generated in this scattering process of the order of b ≈ (1 ~ 2) pT in the frequency range (200 ~ 500) Hz. The lowest eigenmode of subionospheric waveguide (TM (transverse magnetic) mode) exhibits the weakest attenuation at frequencies below 1 kHz and can therefore propagate over large distances. Because of the high conductivity of the Earth near the Earth's surface, the electric field of this mode is directed vertically and a horizontal electric field component appears with an increase in altitude. Its value approaches the amplitude of the vertical component over the spectral range 100-1000 Hz at altitudes of 115 to 120 km, where the conductivity of the ionosphere is at maximum. Horizontal components of the electric field pulses from lightning discharges induce polarization currents at the conductivity inhomogeneities. The radiation from these currents which depends on frequency, propagates in whistler mode upward into the upper ionosphere and the magnetosphere. On board satellites we observe this radiation at the same geomagnetic field lines where plasma density inhomogenities are observed. Blecki et al. (2010, 2011) have observed the intensive ELF radiation in the ionosphere during (1-6) days before several EQs with great amplitude. It was shown that this radiation is correlated in time and space with the heating anomaly observed by NOAA-18 satellite at the eve of a huge EQ in 2008 in Sichuan. Several other mechanisms of the generation of such radiation have been discussed (e.g., see Liperovsky et al., 1992; Molchanov et al., 1993), but our calculations showed that these mechanisms produced much weaker effects than those observed experimentally over the spectral range covering several hundred Hz.

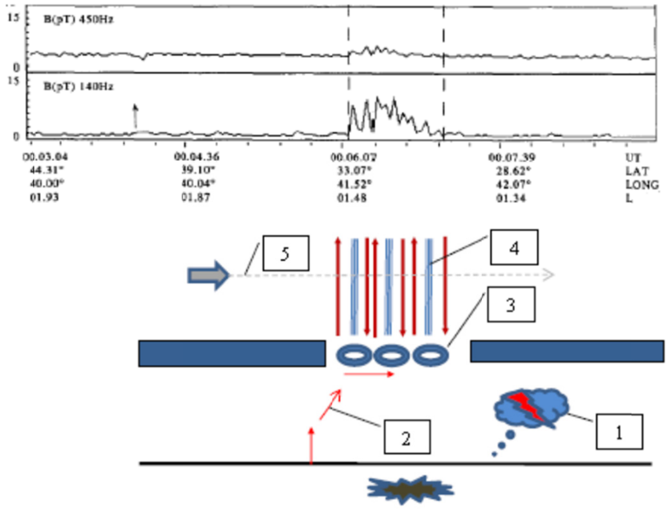

Figure 3. The generation mechanism of electromagnetic ELF wave precursors to EQs (Borisov et al., 1999)

Upper panel: the satellite data on ELF emissions at the frequencies of 140 and 450 Hz in the disturbed magnetic tube (Serebryakova et. al., 1992). Bottom panel: the schema for re-emitted ELF radiation into the upper ionosphere. EM pulses radiated by lightning discharges and propagated in the subionospheric waveguide are scattered by the irregularities of ionosphere conductivity. 1 – Thunderstorms, 2 – Electric field of wave, 3 – Irregularities of ionosphere conductivity, 4 – Plasma irregularities, 5 – Satellite trajectory.

2.3 ULF Electromagnetic Effects

The formation of lithospheric sources of ULF radiation on the Earth's surface and possible propagation of radiation into the ionosphere have been discussed by different workers (Fitterman, 1979; Molchanov et al., 1995; Pilipenko et al., 1999; Molchanov, 1999; Surkov & Pilipenko, 1999; Sorokin and Pokhotelov, 2010a), who considered the physical processes resulting in the electric current generation. Along with the lithospheric sources of ULF radiation it is possible to form the ionospheric sources of radiation stimulated by the perturbation of current in the global circuit at an eve of EQs. Sorokin et al. (2002, 2003) have proposed a mechanism of generation of ULF oscillations in terms of the formation of periodic irregularities of ionospheric conductivity. This mechanism is based on the generation of gyro-tropic waves (GWs) by the interaction of background electromagnetic field with these irregularities. These waves first reported by Sorokin and Fedorovich (1982) propagate within a thin layer of lower ionosphere along the Earth surface in low and middle latitudes with small attenuation and with phase velocities tens to hundreds km/s. Some geophysical effects of GWs are analysed by Sorokin (1988) and Sorokin and Yaschenko (1988). Further development of the theory of these waves was fulfilled by Sorokin and Pokhotelov (2005). The scheme of generation of magnetic field ULF oscillations connected with the propagation of GWs in a conducting layer of the ionosphere is presented in Figure 4. Various sources are capable to generate background electromagnetic noise in ULF range, but the most powerful are thunderstorms. Oscillating noise of the electric field forms the polarization currents by conductivity irregularities in the ionosphere, and these horizontal periodic electric currents with the spatial scale ~10 km are considered as a source of GWs. Generation and propagation of these waves leads to the excitation of narrow band magnetic oscillations in the frequency range of 01 to 10 Hz on the ground, result in an interference effect. Its value in the EQ epicenter reaches approximately 20-25 % above the undisturbed background level. The spectral maximum amplitude decreases in dependence on distance from the EQ epicenter and the spectral maximum frequency decreases monotonously in dependence on the spatial scale of irregularities.

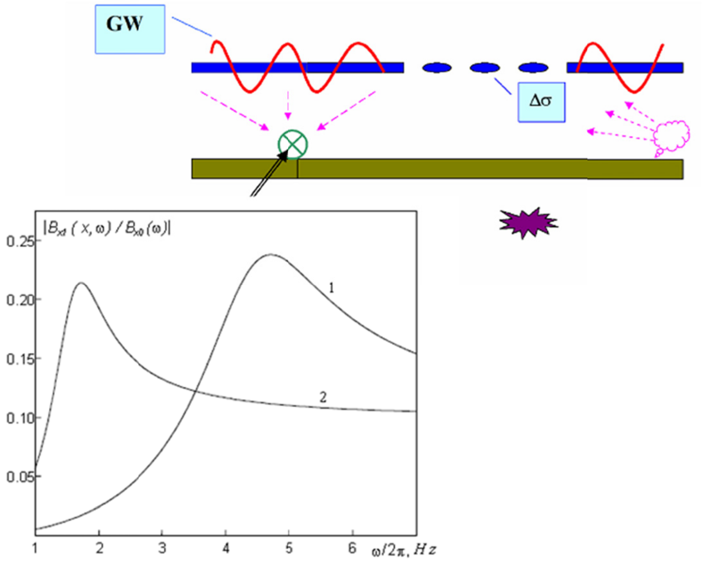

Figure 4. Schema of formation of ULF geomagnetic pulsations generated in the ionosphere (upper panel) and the calculated normalized spectrum of geomagnetic oscillations for the different spatial scale of inhomogeneities (lower panel)

Curve 1 corresponds to the spatial scale of inhomogeneities 15 km; curve 2 corresponds to the spatial scale of inhomogeneities 30 km. (Sorokin et al., 2003)

Sorokin and Hayakawa (2008) have further considered the spectrum of waves generated by irregularities in the layer of Hall conductivity with finite thickness and in the layer of Pedersen conductivity. They obtained a few spectral lines related with the thickness of the layer with Hall conductivity and also the absorption of waves is related to Pedersen conductivity. If the source of waves is located in a horizontal direction with spatial scale, for example, of 100 km, the frequency spectrum of magnetic pulsations to be expected exhibits 6 lines in the ULF/ELF frequency 1-30 Hz as shown in Figure 5. Characteristics of the line spectrum are defined by both the parameters of the ionospheric irregularities and electro-physical parameters of the ionosphere. The amplitude of this magnetic pulsation is basically defined by the intensity of ionospheric irregularities and its spatial structure and absorption of the wave. The frequency of spectral line maxima are determined by the thickness of the conducting layer, and the width of those spectral lines is defined by the width of spatial spectrum of ionosphere irregularities and the ratio between Pedersen and Hall conductivity. The dispersion relation of these waves was considered by Sorokin et al. (2009).

The ground-based measurements yielded the detection of such discrete narrow-band spectra of the ELF electromagnetic oscillations during seismic enhancement, volcanic eruptions or spacecraft flights. Rauscher and Van Bise (1999) found that the spectrum maxima are located approximately at separate frequencies of 2, 6, 11, and 17 Hz, and these processes seem to be associated with the formation of horizontal irregularities of the ionospheric conductivities (Sorokin & Hayakawa, 2008).

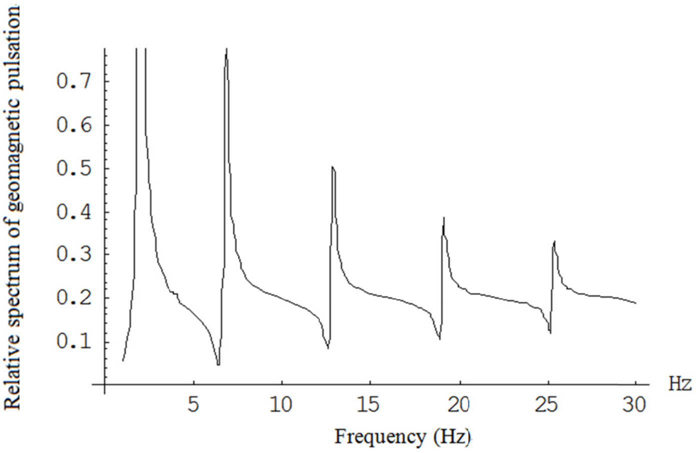

Figure 5. An example of computational results on the frequency spectrum in ULF/ELF band of ionospheric pulsations to be observed on the Earth's surface (Sorokin & Hayakawa, 2008)

Hayakawa et al. (2011b) have observed the excitation of Schumann resonance (SR)-like line emissions possibly related with large EQs. The SR-like line emissions have been detected in Japan in possible association with two huge EQs in Japan. The frequencies of those line emissions are likely to be shifted from the conventional SR harmonics by a significant amount of 1~2 Hz, but their temporal variation seems to suggest a close relationship with the conventional SRs. This phenomenon is interpreted in terms of the ground detection of GWs in the ionospheric dynamo region, being excited by the seismogenic noises from below in the ELF SR band (Hayakawa et al., 2010).

In any conventional approach to many geophysical problems related to ULF magnetic pulsations, the ionosphere is approximated by a layer with homogeneous conductivity, which is connected with the regular conductivity profile integrated over height. However there are some indications that such a simple model is not valid even for ULF frequency range, and we have to take into account the existence of realistic ionospheric perturbations in conductivity. The variations in plasma density can produce, several times, an increase in "effective" conductivity, which is included in the consideration of ULF wave characteristics. Sorokin et al. (2004) consider depression in the intensity of ULF magnetic pulsations, which is observed on the ground surface due to the appearance of irregularities in the ionosphere. It is supposed that oblique Alfvén waves in the ULF frequency range have propagated downward from the magnetosphere through the thin ionosphere with horizontal irregularities of ionospheric conductivity. It is further shown that ULF pulsation intensity can be essentially decreased for frequencies f = 0.001-1.0 Hz in nighttime, but the change is negligible in daytime in coincidence with observational results.

Molchanov et al. (2003) and Schekotov et al. (2006) have reported results of ULF magnetic field observations (0.003- 5.0 Hz) at Kamchatka region during a long period of seismic activation. They found a remarkable and statistically reliable ULF intensity depression several days before strong seismic shocks. This effect was especially clear in nighttime and for the filter channels 0.01-0.1 Hz, but it was absent in daytime. They interpreted the effect in terms of the assumption of AWG intensification induced by changes in temperature and pressure near the ground due to the gas and water release during the course of EQ preparation. Appearance of gravity waves in the ionosphere leads to the occurrence of irregularities and to the change of effective ionospheric conductivity. An alternative assumption as it was shown above is that the changes of ionospheric conductivity is connected with irregularities appeared by AGW instabilities in the electric field and ionosphere heating by the ionospheric current in a seismic region. It seems that theoretical results here coincide with observational data reported by Molchanov et al. (2003).

3. Large-Scale Irregularities of the Ionosphere

3.1 D Layer of the Ionosphere

Electric current perturbation in the global circuit by an additional EMF is accompanied by the ionospheric modification. The model for perturbation of electron and ion densities in the ionospheric D region has been assumed by Laptukhov et al. (2009), who studied the mechanism on the change in electron and ion densities in the ionospheric *D* region due to the electric current flowing in the atmospheric–ionospheric electric circuit. There exists the current disturbance in this circuit over the regions of increased seismic, meteorological, and thunderstorm activities. In the framework of the model, we consider the influence of transportation of the electrons and ions under the action of the electric field on the formation of a disturbance in the *D* region and heating of the plasma electron component by the field. At an intensification of the electric current flowing through the ionospheric *D* region, the stationary vertical distribution of the plasma density at heights of this region is different substantially from its undisturbed distribution. In quiet conditions the value of the background electric current density ~10^{-12} A/m^2 corresponds to this distribution. The changes in the electric current and so in the electric field in the atmospheric–ionospheric circuit during the occurrence of intense processes in the lower atmosphere, might lead to the formation of a disturbance in the spatial distribution of charged particles in the lower ionosphere. This disturbance occurs in the *D* region because of both the transportation of electrons and ions by the electric current and the heating of electrons. Figure 6 depicts the calculation result of spatial distribution of electron density derived by Laptukhov et al. (2009). The downward transportation of electrons by the upward electric current, leads to an increase in the plasma density at heights below 70 km. It happens because electrons have no time to attach to neutral molecules at lower altitudes. For the current density of the order of ~(10^{-9}-10^{-8}) A/m^2, the density of electrons and ions at heights of (50-60) km can increase by an order of magnitude. Then the transportation of charged particles by the electric field plays a more substantial role in the formation of the disturbance than the heating of electrons by this field. With the reverse direction of the electric current, the plasma density in the *D* region decreases as compared with its value in quiet conditions. An increase in the electric field which can reach a value of the order of a few V/m at heights of about 60 km corresponds to the intensification of the quasi-static currents in the ionospheric *D* region.

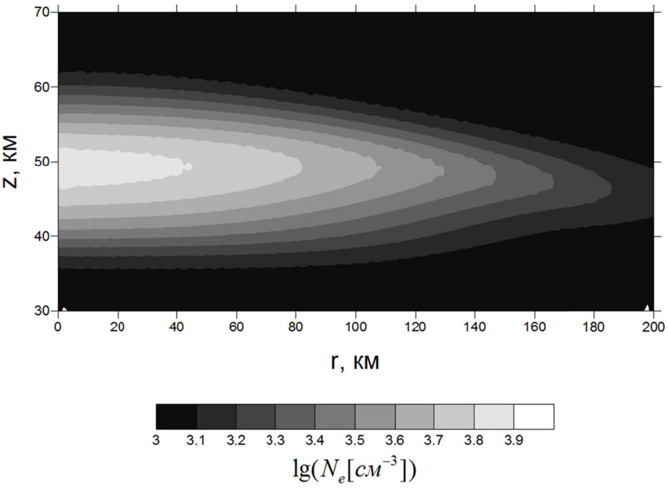

Figure 6. An example of results of calculating the electron density spatial distribution in the ionospheric D region in the case when the electric current flows above a seismic region (Laptukhov et al., 2009)

To investigate ionospheric dynamics during a long time we use the well-known radio-physical sounding methods. Among them are the determination of altitude dependence of electron density by sounding both from below and from above, the Doppler sounding of plasma velocity, the determination of total electron contents (TEC) with the use of GPS (global positioning system) receiver net and the identification of perturbation of the upper waveguide wall on the basis of observation of amplitude and phase of the radio signals. Long-term observations of the ionospheric state by each of these methods reveal the occurrence of different anomalies in the observed signals to be interpreted in terms of the mechanism of the interaction of the current in global circuit with the ionospheric plasma. The data manifesting modification of the ionospheric *D* region over epicenters of future EQs were presented by Hayakawa et al. (2005), Nickolaenko et al. (2006), and Ohta et al. (2006). In these papers anomalous effects were detected at observatories of the SRs near seismically active regions. The anomalies are mainly characterized by a sharp increase in the amplitude of the fourth SR and substantial shift of its frequency (~1 Hz). As far as the parameters of the SRs are governed by the properties of the Earth–ionosphere waveguide, this effect was interpreted as a result of changes in the ionization degree in the *D* layer and changes in the height of reflection and absorption of VLF waves. The available models of disturbance of the *D* layer are based on the use of the equation of photochemical balance of densities of charged and neutral particles forming the plasma at these heights. For example, Martynenko et al. (1996), Grimalsky et al. (2003), and Rapoport et al. (2004) considered a disturbance in the ionospheric *D* region electron density under the action of electric field based on the process of electron heating and changes in the rate constants of recombination and attachment depending on the electron temperature. The shift in the photochemical balance related to this leads to changes in the electron collision frequency, which influences radio wave propagation. It was shown that the electric field at a height of about 60 km should reach 1 V/m in order to explain the observed effect. Laptukhov et al. (2009) consider a model of generation of disturbances in the ionospheric *D* region as a result of charge transportation with flowing of an electric current. The electric field of the flowing currents leads to the transport of electrons and positively and negatively charged ions in the ionospheric *D* region. In the upper part of the layer there exist free electrons, whereas in its lower part there are present negatively charged ions which appear as a result of rapid attachment of electrons to neutral molecules. At the flowing of the electric current, a layer of enhanced electron density is formed due to the transportation and change in the type of charge carriers.

3.2 E Layer of the Ionosphere

The perturbation of electric current in the global circuit is caused by modification of the ionospheric E layer. Sorokin et al. (2006) have shown that the electric current flowing into the ionosphere from the atmosphere leads to an increase in the E layer plasma density, who presents the method for calculating the spatial distribution of electron number density perturbations in the bottom ionosphere due to the appearance of external electric current in the near-earth atmosphere. The origin of plasma density enhancement is that atmospheric electric currents carry positive charged ions upward and magnetospheric field-aligned electric currents carry electrons downward to the ionosphere. Furthermore, the horizontal electric field of conductive current carries negatively charged ions by drift in the ionosphere. Positive ions of the atmospheric conductive electric current flowing into the ionosphere are compensated by electrons of the field-aligned current and negative charged ions by the current flowing along the conducting layer of the ionosphere. As a result, we expect an increase in plasma density in the lower ionosphere. We have derived a system of nonlinear equations for plasma density and electric field in the lower ionosphere at a given electric current in the global circuit. These equations are used for computing the spatial distribution of electron density. Figure 7 illustrates an example of calculation results. Large gradient of electron number density in the bottom boundary of this layer can stimulate the turbulence, which forms the anomalous sporadic-E layer over the disaster region. Drift of the long-lived metallic ions by the electric field of conductive current results in the occurrence of a rather thin layer of electron number density in the lower ionosphere, and this layer can be registered as anomalous sporadic-E layer. Thus, appearance of the external electric current in the lower atmosphere over the region of disasters can lead to the formation of lower ionospheric disturbances including the anomalous sporadic-E layers. The mechanism presented above can be applied to the interpretation of observation data of ionospheric disturbances over the disasters such as EQs, typhoons, nuclear station catastrophes, dust storms and other ones which lead to the formation of an external electric current in the lower atmosphere.

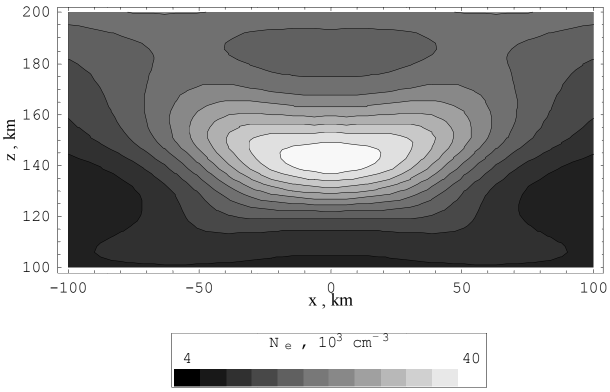

Figure 7. Calculation result of electron number density distribution in the ionospheric E - region disturbed by the electric current flowing above a seismic region (Sorokin et al., 2006)

The growth of seismic-related quasi-static electric field in the ionosphere changes significantly the characteristics of AGWs as shown by Sorokin and Pokhotelov (2014), who have shown that background IGWs (internal gravity waves) propagating from the lower atmosphere up to ionospheric heights are caused by oscillations of the ionosphere. The analysis of the averaged spectra of background perturbations showed the existence of spectral lines. The rule of frequency selection is different from that for a resonator since in each moment one can observe the waves with different frequencies. Only being averaged over a substantially large time domain one can reveal predominance of the waves with specific frequencies. The interaction of the wind in the ionosphere with the geomagnetic field leads to the appearance of Ampere’s force, the vertical gradient of which modifies the features of IGWs (Sorokin & Pokhotelov, 2010b). There arises the discrete spectrum of perturbations with a basic period of 30 min. During EQ preparation in the ionosphere above the epicentral zone there appears the quasi-static electric field with the amplitude of 10 mV/m, which increases the Ampere’s force, formed by the wind. Based on the calculations by Sorokin and Pokhotelov (2014), the wave gas pressure and its normal derivative are continuous for selected periods during the propagation across a conductive layer, where the Ampere’s force operates. This means that the waves with these periods are not affected by this force. The action of the Ampere’s force does not provide the arrest on the waves with other periods. However, the influence of this layer on these waves results in their scattering, so that the waves whose period does not satisfy the condition of propagation across the conductive layer, damp strongly. This leads to predominant growth of the amplitude of perturbations with discrete spectrum, the period of which satisfies such a condition. A calculation result of the period of discrete spectral maxima at the growth of electric field is presented in Figure 8. The increase in the Ampere’s force due to the electric field of seismic origin results in the appearance in the spectrum of ionospheric oscillations of maxima with short periods of the order of 10 and 22 min. They are really observed in the experiments.

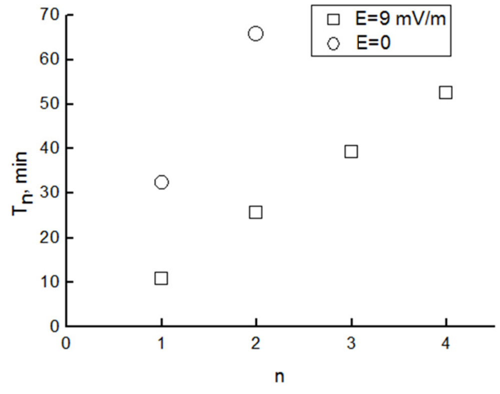

Figure 8. The values of periods corresponding to spectral maxima of oscillations in the lower ionosphere. Circles – the electric field is zero, and squares – the electric field equals 9 mV/m (Sorokin & Pokhotelov, 2014)

For the study of long-term ionosphere dynamics, we use special well-tested radio-physical methods. In some studies (e.g., Biagi et al., 2004; Rozhnoi et al., 2005, 2007; Hayakawa, 2007) the specific variations of the amplitude and phase of VLF signals were observed, the traces of which were close to the epicentres of the forthcoming EQs. The transmitters and receivers of these waves (20-50 kHz) propagating in the Earth-ionosphere waveguide were located on the ground. Such anomalies arise before an EQ with magnitudes M > 3 3-10 days before the event. The characteristics of propagation of VLF/LF (VLF, 3-30 kHz, LF, 30-300 kHz) signals in the Earth-ionosphere waveguide are defined on one hand by the electric conductivity of the Earth's surface and on the other hand by the conductivity of the lower ionosphere. The conductivity of the Earth's surface is of a minor effect to the variation. The observed perturbations in the signal are mainly dependent on the condition of reflection height; the value of electron density and its gradient near the boundary of the lower ionosphere. The extensive review of the action of seismic processes on the lower ionosphere was given by Hayakawa (2007), who presented the proofs of existence of the ionosphere perturbations related to the EQs using a statistical analysis and separate case studies. The change in the position of characteristic minima in the diurnal course of phase and amplitude during sunrise and sunset a few days prior strong EQs in Japan was presented in the papers by Hayakawa et al. (1996) and Molchanov and Hayakawa (1998). Biagi et al. (2004) give the data of the signal level in the VLF/LF range propagating along the five traces. The explicit decreases in the signal intensity before the EQ epicenters which were close to the traces of the signals were found. Rozhnoi et al. (2005) analyzed the signals of a transmitter (40 kHz) located in Japan from 01.07.2004 to 24.01.2005, and the receiver was located in Kamchatka. A series of EQs appeared during this time near the signal propagation trace. They have shown that during a few days prior to the EQs in each series there were anomalies in the form of decreases in the amplitude and phase of the signals. The spectra of perturbations were also analyzed, which have shown that in the spectra on quiet as well as disturbed days the main maxima correspond to the period of 30-35 min. Moreover, during seismic activity there is evidence of appearance of maxima with 20-25 min and 10-12 min. It should be noted further that the analysis of spectra of amplitude and phase variations during magnetospheric substorms does not reveal such an effect. Rozhnoi et al. (2007) presented further observations of VLF/LF amplitude and phase perturbations propagating along three wave traces together with DEMETER satellite data during two periods of seismic activity in Kamchatka-Japan region. They found explicit anomalies in the characteristics of signals on the ground and on board the satellite during a period of seismic activity. Perturbation of the conductive current in the global circuit above the seismic region is considered to trigger such modification of the altitude profile of electron concentration, which is the cause of the appearance of anomalies of the signals in the VLF/LF range. As the confirmation of such a possibility the data obtained by Fux and Shubova (1995) during Chernobyl accident may help. They have shown that strong discharges of radioactive substances and aerosols into the atmosphere was accompanied by the variation of the phase and amplitude of the VLF signal along the propagation trace that passes the region of the accident. An analysis carried by Martynenko et al. (1996) showed that such perturbations of the characteristics of VLF propagation may arise due to the increase in the electric field in the lower ionosphere boundary up to the value ~1 V/m. Along with the rearrangement of the altitude profile of plasma density in the upper ionosphere above a seismically active region, the formation of sporadic layers in the lower ionosphere has been really observed (Ondoh & Hayakawa, 2002; Ondoh, 2003). The critical frequency of the sporadic E layer, f_0E_s, reached 8~9 MHz in daytime, which corresponds to a number density of electrons $\sim 10^6$ cm^{-3}. High-altitude rocket measurements in the medium-latitude ionosphere showed that the electron number density in the sporadic layer was 2×10^5 cm^{-3}, and the electric field in this layer reached 10 mV/m (Yokoyama et al., 2002). It was an attempt to explain the sporadic E layer occurrence by radon injection in the atmosphere, in which they assumed that radon is transferred to the top of a cloud with low temperature and it produces the positive charged ice crystals. While the bottom part of the cloud is charged negative. Such a sporadic layer is generated as a result of electrostatic ionization of lower ionosphere by electric discharges in the cloud. Liperovsky et al. (1997) and Meister et al. (2002) considered the mechanism for sporadic layer formation by acoustic and internal gravity waves. However, the above-mentioned model for the formation of ionospheric irregularities by electric current disturbances on the global circuit is coordinated with other numerous plasma and electromagnetic data.

3.3 F Layer of the Ionosphere

Perturbation of electric current in the global circuit over a seismic region leads to significant modification of the ionospheric F layer registered as the variation of TEC (Sorokin et al., 2012c; Ruzhin et al., 2014). The TEC variation is defined by the plasma concentration change in the ionospheric F layer in the altitude interval (200 – 1000) km. For the TEC calculation we take into account just the sufficient vertical transport of charged particles only due to the smallness of horizontal derivatives of macroscopic parameters. As follows from observational results the horizontal scale of ionospheric perturbation is of the order of 1,000 km which is significantly exceeding the vertical scale of altitude distribution of electron concentration. The plasma drifts in the electric field results in a TEC growth and a decrease in the disturbed region. The TEC formation in this case is schematically depicted in Figure 9. This figure shows that if the field is directed to the east the plasma drift has an upward direction, and that in the zone where the field is directed to the west we expect the downward direction of plasma motion. Calculation results show that the value of field connected with the disturbed current in the global circuit exceeds the background value by several times, so that the plasma drift in such a field results in a significant change in TEC. One should keep in mind that appearance of the electric field in the ionosphere leads not only to plasma drift in the F layer. As it was shown by Sorokin and Chmyrev (1999b), the increase in electric field and heat emitted in the E layer of ionosphere leads to the growth of temperature of F layer, forming the F layer. The heat flux emitted in a thin conducting layer in the horizontal electric field with the value 6 mV/m is of the order of (10^{-4}~10^{-3}) W/m^2. Whereas the conventional heat flux emitted by the absorption of solar radiation in the ionosphere (~100km) is of the order of 10^{-3} W/m^2, which varies depending on solar cycle. Consequently, the heat emitted by the electric current in the ionosphere above a seismic zone contributes a significant part of general heat in the ionosphere. Heating of the ionosphere by the electric current increases the scale of altitude distribution of ionospheric components and, consequently, the altitude distribution of ionosphere F layer. It leads to the spatial distribution of TEC perturbation with one sign in all the seismic zones. Figure 9 illustrates the scheme for the formation of TEC perturbation connected with ionospheric heating by the electric current. Heating of the upper layers of the ionosphere located above the bottom ionospheric layer (120 – 150) km with electric current is realized by the upward transport of heated gas. Calculations by Sorokin et al. (2012c) show that the ionospheric heating by the electric field with amplitude 6 mV/m may lead to relative TEC changes of more than ten percent. Total spatial distribution of the TEC perturbation is determined as a result of influence of these two effects and their characteristics depend on the ratio between them. Our calculation shows that an increase in aerosols concentration near the Earth's surface by several times leads to a relative TEC variation of several tens of percent. A further calculation result of the horizontal distribution of ionospheric temperature as a result of the ionospheric heating by the perturbation of electric current is presented in Figure 10, in which the spatial distribution of TEC perturbation is due to a combined effect of the ionospheric heating and drift. The characteristics of perturbation depend on the ratio between these effects and the example of calculation results shows that a reasonable quantity of injected aerosols in the atmosphere is accompanied by the TEC perturbation of observed amplitude.

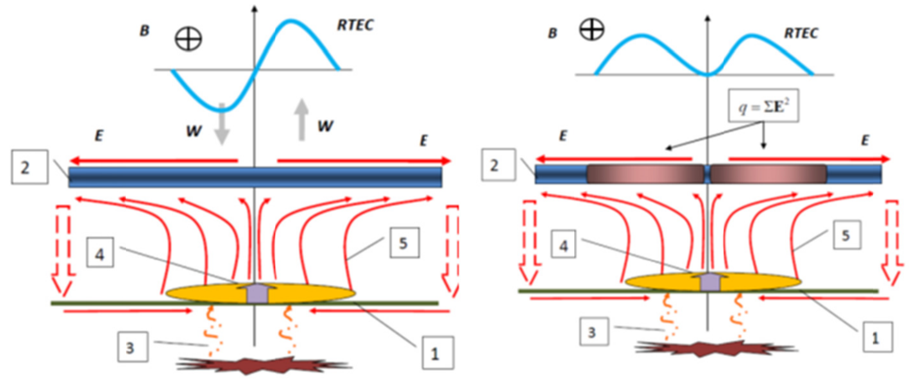

Figure 9. Schematic illustration of TEC disturbance due to plasma drift in the electric field (left panel) and heating of the ionosphere by electric current (right panel)

In the figures RTEC is the relative total electron contents. 1. Earth's surface. 2. Conducting layer of the ionosphere. 3. Injection of charged aerosols by soil gases. 4. Region of EMF formation in the near ground atmosphere. 5. Perturbation of electric current in the global circuit

The method for measuring TEC using GPS receivers has achieved significant progress lately. The analyses of TEC spatial distribution have been carried out, for example, by Liu et al. (2001) and Zakharenkova et al. (2007, 2008). Their observations indicate that there is possible both the growth and depletion of TEC. Computation simulations show that observed TEC variations can be appeared when the electric field attains a value (1~10) mV/m in the ionosphere at EQ preparation. At the same time, there are absent visible changes of electric field on the Earth's surface of a seismic region when we detect the TEC perturbation. Such changes of electric field are possible only as the result of perturbation of the electric current in the global circuit due to the injection of charges aerosols in the atmosphere by soil gases (see details in Sorokin and Hayakawa (2013)). Turbulent and convective transport of the aerosols and their gravitational sedimentation in the atmosphere, are found to form an EMF. Inclusion of this EMF in the global circuit is a cause of electric current perturbation there, and this EMF is found to drive the mechanism of seismicity transmission into the ionosphere.

Another mechanism of seismic-related TEC formation was considered by Kuo et al. (2011), who assumed that ionospheric density variations can be caused by Earth's surface charges/currents produced from electric currents associated with the stressed rock (Freund, 2009). The stressed rock acts as a dynamo to offer currents for the global circuit. Their simulation results show that a current density ~ (10^{-7}~10^{-6}) A/m^2 at the EQ fault zone is required to yield daytime TEC variations of 2–25 %. However, the vertical component of electric field on the Earth's surface should be ~ (10^7~10^8) V/m to obtain the current with such a value. This is in contradiction with the observation data, because there are absent such a field in a seismic region. Really, the field is not exceeding their background value of the order of 100 V/m in a seismic region when we observe the TEC perturbation. Moreover, the duration of hole current with such a value in the stressed rock is only several tens of minutes, which is significantly less than the existing time of TEC perturbation.

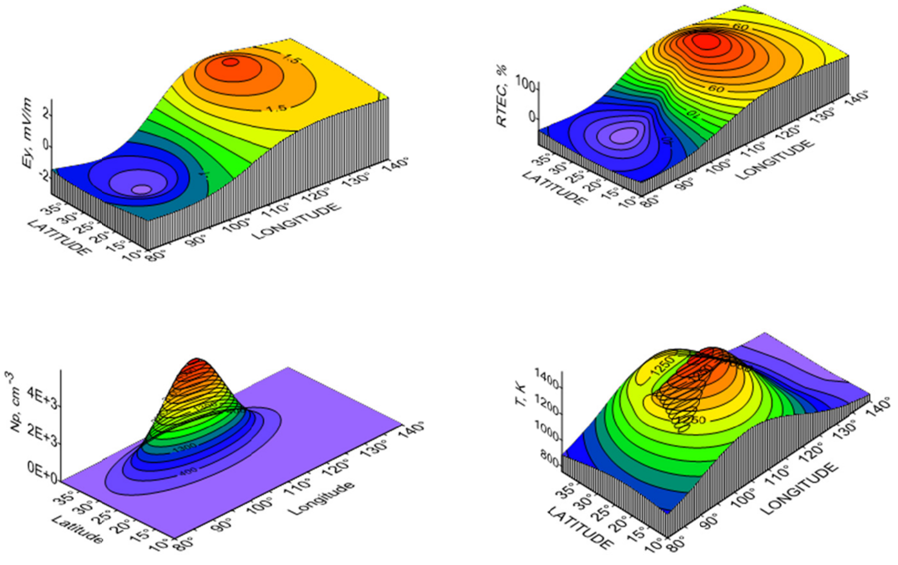

Figure 10. Calculation results of the TEC spatial distribution (upper right panel) and electric field (upper left) in the ionosphere (upper left) at a given distribution of charged aerosols concentration on the Earth's surface (bottom left)

The TEC perturbation is resulted from combined effects of ionospheric heating (bottom right) and plasma drift (Sorokin et al., 2012c).

4. Breakdown Electric Field in the Troposphere

It has been shown (Sorokin et al., 2011, 2012a,b) that the quasi-static electric field reaches a breakdown value in the atmosphere at altitudes (5 – 10) km over an epicenter of preparing EQs. The disturbed region has a horizontal scale over 100 km, and the vertical scale is of the order of 1 km. The atmospheric turbulence leads to the appearance of random electric discharges, and any disturbance of atmosphere density in the turbulent cells might result in the occurrence of local breakdown electric field and electric discharges. We have developed a theory of generation of electromagnetic radiation by random electric discharges, in which we obtained the equations of electromagnetic field of radiation generated by the troposphere region with random discharges. Calculations of the spectrum of electromagnetic radiation behind the horizon from the epicenter of seismic region are derived, which shows the frequency dependence of power spectrum of radiation at a distance of 300 km from the epicenter of disturbed region in Figure 11. The electric current of random discharges is found to excite electromagnetic radiation in the range of 10-100 MHz with amplitude 6μV/m. The value of spectrum maximum depends on the occurrence frequency of discharges and their shape depends on the time scale of current wave build-up and the slope in the discharge. The scattering of VHF electromagnetic waves by random electric discharges occurring in the troposphere over a seismic region has been considered in Sorokin et al. (2014), which are caused by disturbances of electric current in the global atmosphere–ionosphere circuit. It is shown that the electric field of disturbed current can reach a breakdown value at the altitudes 5-10 km. The method for computing the mean value of electromagnetic wave fields scattered by the random discharges has been elaborated, which shows that the electric field of scattered wave exceeds significantly that of diffracted wave over the horizon. Figure 12 illustrates the scheme for wave propagation over the horizon, in which the signal of a VHF transmitter is scattered by the discharges because they have a significant electric conductivity. It is shown that the signals of a VHF transmitter are scattered in the level of troposphere with random discharges which are located at the altitudes from 5 up to 10 km. The thickness of this level is of the order of a few km. The scattered field is propagated over the horizon with respect to the transmitter. The scattered wave is found to exhibit spectral line broadening $\Delta f_0 \sim 1/t_0$ if the transmitter wave is monochromatic. That is, the spectral broadening of scattered wave is connected with the temporal dependence of discharge conductivity (t_0, its temporal scale) and it can have a value of the order of (0.1 – 1) kHz. Based on our elaborated theory the spatial distribution of mean value of scattered wave electric field over the horizon has been calculated, and the result is depicted in Figure 13. We show that the radiation amplitude increases significantly during EQ preparation if its epicenter is located in the vicinity of signal propagation path.

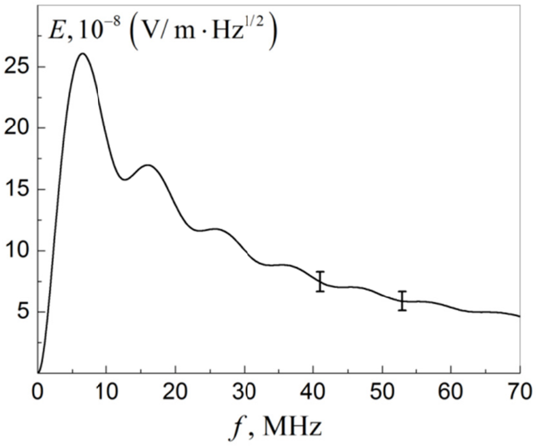

Figure 11. Spectrum of electromagnetic radiation at distance 300 km from the epicenter. The vertical sections of line denote the experimental data (Sorokin et al., 2011)

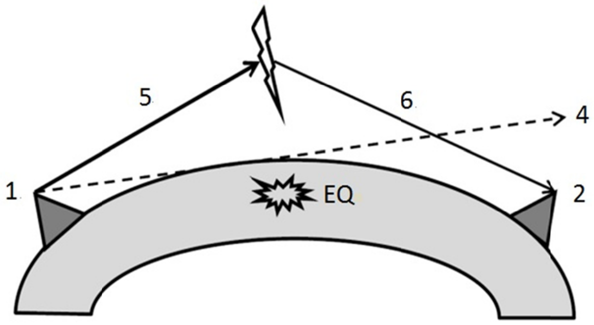

Figure 12. Scheme of the VHF transmitter signal propagation due to the scattering by the electric discharges

1. Transmitter. 2. Receiver. 3. Electric discharges in the troposphere. 4. Direction of diffracted wave propagation. 5. Direction of incident wave propagation. 6. Direction of scattered wave propagation (Sorokin et al., 2014).

The results of above-mentioned theory are confirmed by the observational data of seismic- related VHF radio emissions and VHF transmitter signals over the horizon during EQ preparation. Observational data of the seismic-related VHF radio emissions at 41 and 53 MHz obtained at the four stations of Create Island are presented in Figure 11. The epicenter of EQs is located at the distance more than 300 km behind the horizon, and it was then shown that VHF radiation is generated at the altitudes 1 – 10 km in the atmosphere over the epicenter of EQs. VHF electromagnetic EQ precursors were registered by a network of four stations of Create Island (Nomicos et al., 1995; Vallianatos & Nomicos, 1998). Since 1992 a special network of telemetric stations were established on this island for the investigation of electromagnetic precursors. At each station the VHF radio noise at the two frequencies of 41 and 53 MHz, is measured as one of different parameters. These radiations are found to have occurred for several days before an EQ, and their duration reaches several days. If VHF electromagnetic radiation is propagated over the distance more than a wavelength λ≈6~7.5m, the condition of optical propagation is fulfilled, and consequently it is possible to receive the signal at a distance of the order of 300 km just in case when its source is located in the atmosphere above Earth's surface. According to Ruzhin et al. (1999) and Ruzhin and Nomicos (2007), the region of generation of VHF electromagnetic radiation is at the altitudes of the order of several kilometers above EQ epicenters located behind the horizon. The frequencies 41 and 53 MHz of radio waves had been chosen for electromagnetic monitoring on Create Island because the signal-to-noise ratio is an optimal one for this frequency range. Noise analyses by Ruzhin and Nomicos (2007) allow them to conclude that observed signals were generated by the seismic origin, and these observation data are found to be consistent with the calculation result by Sorokin et al. (2011). Registration of the VHF transmitter signals over the horizon shows that their amplitude increases significantly during EQ preparation if the epicenter of a coming EQ is located in the vicinity of signal propagation path. The result of observations indicates that the tropospheric region influences the signal propagation over a seismic zone; that is, the anomaly in signal propagation is observed during several days before an EQ. The observed anomaly in the signal propagation of VHF transmitter at the eve of an EQ is explained by the generation of scattered field over the horizon. The analysis of VHF transmitter signals over the horizon was also carried out by Fukumoto et al. (2001), Kushida and Kushida (2002) and Yasuda et al. (2009), and significant growth in the signal amplitude is observed if the propagation path is located over the seismic region. Fukumoto et al. (2001) confirmed that the anomalous propagation events were the result of scattering of VHF-band radio waves in the troposphere immediately prior to an EQ, by documenting reception at an observatory that was beyond the line of sight of transmission location. Pilipenko et al. (2001) showed that the received intensities of scattered waves were stronger when the antenna was at a shallower angle, which implied that the scattering body was in the middle atmosphere rather than in the ionosphere. This conclusion was then found to be consistent with the sophisticated direction finding result by Fukumoto et al. (2001). Hayakawa et al. (2006, 2007) have proposed a generation mechanism of atmospheric disturbances resulting from changes in geochemical quantities associated with EQs and VHF radio wave refraction. Yonaiguchi et al. (2007a,b) discussed that the effect of long-range VHF wave propagation is usually due to the meteorological radio ducting, and Moriya et al. (2010) and Devi et al. (2012) have additionally observed the anomalous VHF-band radio-wave propagation beyond the line of sight prior to EQs. Radio waves transmitted from a given FM radio station are considered to be scattered in such a way that they could be received by an observation station beyond the line of sight. The results of calculations provided by Sorokin et al. (2014) are confirmed by the reports of observation of VHF transmitter signals over the horizon propagation during EQ preparation.

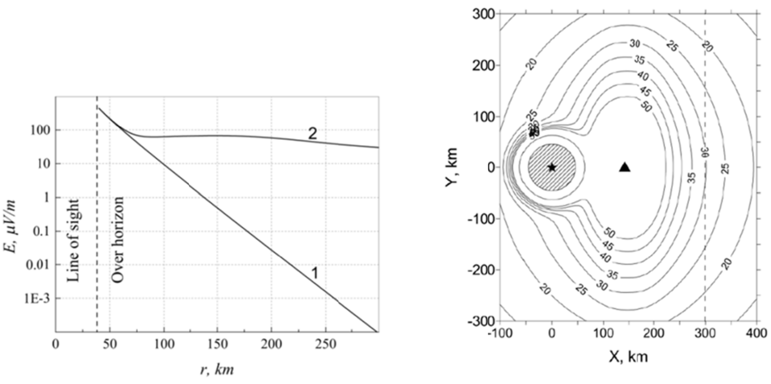

Figure 13. Calculation result of the spatial distribution of VHF transmitter electric field propagating over the horizon due to their scattering by electric discharges in the elliptical tropospheric region (Sorokin et al., 2014)

One can consider that the disturbed region may be a source of other phenomena; the glow of discharges region and the atmospheric heating of the disturbed region (Sorokin et al., 2012a). Figure 14 presents the scheme of possible phenomena. The glow consists of optical radiation of electric discharges in the disturbed region, and the estimation of possible glow level of disturbed region over an epicenter of preparing EQ gives approximately 9 kR. This quantity corresponds to the radiation of polar glow with middle intensity, while the glow of night time sky is 250 kR for the sake of comparison. The occurrence of breakdown electric field in the troposphere leads to the Joule heating of the disturbed region over a zone of EQ preparation. Further estimations show that the conductivity current is at a value (10^{-8}-10^{-7}) A/m^2, which leads to the energy dissipation of electric current in a unit volume and a unit time reaching 3×(10^{-3}-10^{-2}) W/m^3 at the altitude of the order of 10 km. So, the heating rate amounts to (0.5-5.0) K/day at these altitudes. To determine the stationary value of temperature we have to take into account the heat conduction and convection. Above-presented estimations show a possibility of occurrence of considerable phenomena in the atmosphere over the zone of EQ preparation. The occurrence of electric discharges in the troposphere results in the growth of ozone concentration and the generation of microwave radiation. These electromagnetic and optical phenomena can be observed on the satellites, which serve as the sources of information on the development of seismicity. Results of theoretical researches are confirmed by the observation of influence of lithospheric activity one the atmosphere and ionosphere. Based on the radio-locator data, Voinov et al. (1992) revealed the appearance of distributed electric charges above the epicenter 1 – 3 days before the Spitak EQ, and that the area of charges distribution was different from those occurred during thunderstorms. The glow of sky at a distance of 100 – 200 km from the epicenter on the eve of a powerful EQ (M=7.3) in China was observed at night (Zhao & Qian, 1997). Williams (1989) then noted that the seismic related airglow can reach altitudes more than 1 – 2 km at distance 140 km from the epicenter. The growth of ozone concentration was observed approximately at the same time before EQs (Tertyshinikov, 1996). There have been observed outgoing long wave (8-12 μm) radiation anomalies in the atmosphere (10-12 km) with the thermal flux intensity from 4 to 80 Watts per square meter in the zones ~2.5 degrees in latitude and longitude over an EQ region a few weeks to a month before a large EQ (Ouzounov et al., 2007). Outgoing long wave radiation can be generated by the ozone emission (Kratz & Cess, 1988) and heating of the tropospheric layer in which the electric field attains a breakdown value. In this work they used the NOAA/IR(infra-red) data to differentiate between the global and seasonal variability and the transient local anomalies. Thermal anomalies before strong EQs are further discussed by Tronin (2002, 2006) and Tronin et al. (2002).

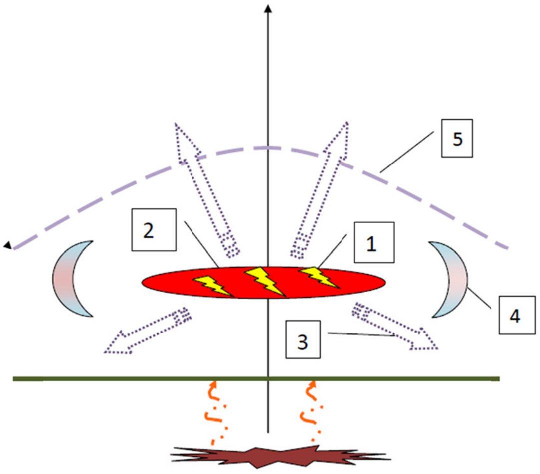

Figure 14. Phenomena accompanying random electric discharges in the troposphere

1. Chaotic electric discharges. 2. Heating of the atmosphere in the discharge region, growth of ozone concentration and the generation of outgoing long wave (8-12 μm) radiation. 3. Broadband electromagnetic VHF emission. 4. Airglow in visible range of wavelengths. 5. Refraction and scattering of VHF radio waves in the troposphere providing the over-the-horizon reception of ground-based VHF transmitter signals.

5. Conclusion

Both regions of atmosphere and ionosphere are a united environment, in which the physical phenomena are related with each other. Intensive processes in the lithosphere and lower atmosphere give rise to electrodynamical influence onto the ionospheric plasma. Among them are impending EQs, volcanic eruption, typhoons, thunderstorms, anthropogenic disasters. According to the LAI (lithosphere-atmosphere-ionosphere) coupling model, the growth of electric field in the ionosphere is caused by the formation of an EMF and the variation of electro-physical characteristics of the lower atmosphere connected with the injection of aerosols and radioactive substances with soil gases in a seismic region. In the frame of this model, the theoretical investigations of plasma and electromagnetic effects caused by the current generation in the global circuit have been derived, and the corresponding calculation results show that the EMF occurrence in the global circuit results in a set of plasma and electromagnetic phenomena. An increase in the electric field amplitude leads to AGW instability in the ionosphere. Exponential growth of AGW amplitude in the ionosphere is limited by the formation of vortexes, and as a result the horizontal irregularities of conductivity are generated in the ionospheric E layer. The interaction of ambient electric field and irregularities may result in the generation of field-aligned currents and plasma irregularities elongated along the magnetic field. Such plasma irregularities and field-aligned currents are caused by magnetic field ULF oscillations, electron density fluctuations, spectral broadening of VLF transmitter signals registered on board a satellite. Elongated plasma irregularities are likely to work as ducts and change the whistler characteristics. Scattering of the thunderstorm electromagnetic pulses by the horizontal irregularities of conductivity in the lower ionosphere is caused by an increase in ELF radiation registered by satellites and generation of GWs propagated along the ionospheric E layer. Their propagation is known to form the discrete line spectrum of ULF electromagnetic oscillations and changes the maximum frequency of SR. Moreover, the occurrence of irregularities in the night ionosphere results in the depression of ULF pulsations (magnetospheric downgoing Alfvén waves). The growth of electric field up to the breakdown value in the troposphere is likely to be caused by random electric discharges, VHF radio emissions generated in the troposphere over the seismic region and propagation of the signals of a VHF transmitter by scattering by the discharges behind the horizon. Generation of the electric current in the global circuit is accompanied by the ionospheric modification. First perturbation in the ionospheric D layer is generated by the electron and ion transfer and electron heating caused by the variation of current in the global circuit. The growth of electric current then leads to an increase in plasma density in the ionosphere E layer and the formation of sporadic E layer. The plasma drifts in the electric field and the increase in heat released by the electric current might lead to the modification of TEC in the F region. The theoretical investigation of above-mentioned phenomena allows us to interpret the observational data of significant amount of electromagnetic and plasma EQ precursors in terms of effects of an electric current perturbation in the global circuit.

An electrodynamical model of LAI coupling can be used as a basis of investigation devoted to the search of EQ and typhoon precursors (Sorokin & Cherny, 1999; Chmyrev et al., 2013). The model links associated electromagnetic and plasma satellite data with electro-physical and meteorological characteristics of the lower ionosphere during impending disasters. The model enables us to attribute numerous phenomena in the space plasma to a single cause; namely the variation of conducting electric current in the global circuit.

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