

A Review on Electrodynamic Influence of Atmospheric Processes to the Ionosphere

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Abstract

This work is an attempt to critically analyze the existing theoretical models of the impact of earthquake preparation processes on the state of the earth's atmosphere and ionosphere in the zone of growing seismic activity, as well as the mechanisms of formation and transfer of disturbances in various media over the earthquake center. The determining factor (criterion) of the analysis is the degree of compliance of the simulation results with experimental data obtained at various phases of earthquake development by direct and remote diagnostic methods using ground and aerospace technologies. The key role is played by the model's compliance with the results of measuring electric fields and currents in the near-ground atmosphere and ionosphere, small-scale ionospheric inhomogeneities and correlated field-aligned currents and electromagnetic ULF/ELF emissions. A full-fledged model should also explain the origin of such seismic related phenomena as the generation in the troposphere and over-horizon propagation of pulsed VHF radiation, thermal effects and associated IR emissions as well as the modification of plasma distribution in the D, E and F layers of the ionosphere. The use of this criterion in the analysis allowed us to identify a theoretical model that most fully describes the totality of the above-mentioned experimental data within a single physical mechanism. This is an electrodynamic model based on the perturbation of the conductivity current in the global atmosphere—ionosphere electric circuit due to the injection of charged aerosols into the atmosphere during the preparation and development of an earthquake. The present paper describes this model and the formation mechanisms of related phenomena in the atmosphere and ionosphere, which can be considered as short-term precursors to earthquakes.

Keywords

Earthquake (EQ) Precursors, Charged Aerosol Injection, Global Electric Circuit, Ionospheric Irregularities, ULF/ELF Electromagnetic Emissions, Random Discharges Radiation, Over-the-Horizon VHF Propagation

1. Introduction

Seismic phenomena in the area of earthquake (EQ) preparation stimulate a chain of processes that affect the atmosphere and form (initiate) electromagnetic and plasma disturbances in the ionosphere. In order to understand the nature of numerous electromagnetic and plasma precursors to EQs, it is necessary to study an entire chain of physical processes involved in the generation and the transfer of disturbances from a seismic source into the atmosphere and the ionosphere. The result of this study should be the comprehensive theoretical model describing the formation and interconnection of all the elements of this chain. Until recently there were two major hypotheses placed on the basis of lithosphere-atmosphere-ionosphere (LAI) modeling, which are related to 1) acoustic gravity waves (AGWs) and 2) the electric field [1]. Without going into detail, let us consider first hypothesis for influences to the ionosphere.

Authors of [2] gave the analyses of plasma density irregularities excited in the ionosphere several days before strong EQs. They believed that the occurrence of these irregularities is connected with the AGW propagation through the ionosphere. The source of AGWs could be the long wave earth oscillations, the local green gas effect or an unsteady injection of lithospheric gases. The most effective mechanism is related to the growth of lithospheric gas emanation into the atmosphere. The authors supposed that the AGW generation should be considered as a mechanism for LAI coupling because the atmosphere stratification favors the wave amplification as it propagates upward. Further they discussed various likely scenarios of the development of accompanying processes in the ionosphere. Authors of [3] presented a general concept of the role of AGWs in the LAI coupling. The perturbation of air temperature and density in the atmosphere could follow the pre-seismic hot water and gas releases resulting in the generation of AGWs with the periods in a range of 6 - 60 min. Seismo-induced AGWs could lead to the ionosphere turbulence [4] and the over-the-horizon VHF radio wave propagation in the atmosphere [5]. Among the possible AGW effects are the perturbations of VLF/LF waves in the lower ionosphere [6] and the depression of ULF emissions of magnetosphere origin observed on the ground [7]. However, there are definite difficulties in the interpretation of some observational results in terms of IGW (internal gravity wave)/AGW propagation model. One of them is connected with the fact that these waves propagate angularly to the Earth's surface, and the angle depends on wave period. So, IGW reaches the ionosphere at a distance of the order of 1000 km from the EQ epi-

center, that seems to be in conflict with the localization of plasma and electromagnetic disturbances in the vicinity of EQ epicenter. Nevertheless, an interest in this AGW channel in the LAI coupling still remains [8]. A summary of recent results can be found in [9]. Another hypothesis of the impact on the ionosphere of catastrophic phenomena in the atmosphere is associated with the formation of an electric field and its penetration into the ionosphere [10]. A comparative analysis of these two mechanisms of seismic related influence to the ionosphere is presented in our paper together with some other most interesting ideas concerning the nature of atmosphere-ionosphere coupling effects. A basic initiating role in LAI coupling belongs to intensification of water, gas and heat flows into the atmosphere in fault areas at the stage of EQ preparation. Section 2 describes the observational data on atmospheric disturbances caused by these flows on the eve of an EQ, including an enhancement in number density of charged aerosols and the increase in atmosphere radioactivity. Generation of DC electric field in the disturbed atmosphere and its penetration into the ionosphere is discussed in Section 3. The reaction of the ionosphere to the penetration of an electric field including the formation of large-scale irregularities of the ionosphere, the excitation of small-scale plasma inhomogeneities, non-linear vortex structures and related magnetic field-aligned currents are considered in Section 4. Electromagnetic phenomena observed in ULF, ELF, VLF and VHF ranges on the ground and onboard the satellites over seismically active zones are described in Section 5 together with the generation mechanisms in terms of DC electric field impact on lower atmosphere and the ionosphere. Outlined is the formation of breakdown electric field at the altitude from 1 to 10 km in the atmosphere, which initiates electrical discharges and pulsed VHF emissions observed as “over-the-horizon” earthquake precursors at the distance ~300 km. Generation of ELF precursors is associated with scattering of lightning discharges radiation propagating in the sub-ionospheric waveguide by the small-scale plasma inhomogeneities excited in E-layer due to AGW instability in a presence of over-threshold electric field. An interpretation of seismogenic ULF and VLF disturbances is also described. Summary of the results outlined in the review and the advantages of the comprehensive electrodynamic model of short-term earthquake precursors are presented in Section 6.

2. The Disturbances of the Atmosphere in Areas of Catastrophic Events

In a process of EQ preparation, there rise fluids in the lithosphere, which are a convective flow of water, gas, and heat. The main ways of fluid movement are faults. The composition of the gases released in the fault zones include CO₂, H₂, CH₄, and He. Authors of [3] present the concept of mechanisms for generating various phenomena in the atmosphere and ionosphere. The authors believe that the movement of deep fluid can displace hot water and gas up to the ground surface and cause EQs in the area of their preparation. The timing of the ap-

pearance of fluids and their coordinates has random values, so the EQs themselves, their geochemical anomalies and foreshocks are random events. Perturbations in the temperature and density of the atmosphere occur as a result of the rise of hot water and gas on the eve of an EQ. Summing up, it is possible to formulate the mechanism of influence of EQ preparation process on atmosphere. In the process of preparing an EQ in the epicenter zone and surrounding tectonic faults fluids begin to be released. Depending on the geological situation, depth and magnitude of the impending EQ, a mosaic of precursors is formed on the surface. Hot gas is injected into the atmosphere, the density of which is less than the density of air, and water vapor. As a result, thermal anomalies are formed, the stability of the atmosphere falls, and followed by convection. The yield of soil gases in a seismic region is enhanced during EQ preparation [11]. The intensification of these processes is observed on land in close proximity to faults. Similar processes occur in the vicinity of underwater faults. Direct observations revealed an intense rise of gas bubbles in the marine environment [12] [13]. The results of analysis of natural gas emanations show a clear magmatic origin for CO₂ and He in the water. The distribution of magmatic gases suggests that the areas concerned are still subject to volcanic activity at depth [14]. The results of combined studies in the areas of the occurrence of gas-fluid emanations in the water column, on the seafloor, and in the upper part of the sedimentary section on the northeastern slope of Sakhalin Island were summarized [15]. The phenomena typical of methane seeps were characterized in detail: the presence of acoustic anomalies, high concentrations of methane in the water and sediments.

The presence of an electric charge of gas bubbles in the marine environment results in a double charged layer near the surface of the bubble at the air-water interface. Shells of gas bubbles in water are negatively charged. The charge of the bubble is (10^{-14} - 10^{-13}) C [16]. As a result of the bubble popping and its rupture, the surface of its double charged layer is sharply reduced. When there is a bubble burst, two types of droplets are released from the surface of the marine environment into the atmosphere: small and larger ones. Small droplets are the remnants of the surface film of the bubble, in contact with the atmosphere. Larger drops fly out from the bottom of the bubble. Large drops, having a larger mass, soon fall back into the water. The remaining much smaller film droplets from aerosols in the atmosphere. When we have air bubbles burst, an electric charge is transferred to the atmosphere [17] [18].

The air-sea flux trace gases and their transformation to aerosols and cloud condensation nuclei may be fundamental to cloud formation in the marine environment. Clouds and aerosols have an important influence on the radiative balance of the earth. The local coupling of air-sea fluxes and the formation of aerosols and clouds over the ocean is still highly uncertain. The study combined directly measured air-sea fluxes with satellite aerosol remote sensing was done by [19]. It is a novel, interdisciplinary approach where results from air-sea gas transfer are combined with atmospheric chemistry satellite remote sensing using

meteorological transport models. These results strongly support a local influence of marine-derived aerosol precursors on cloud condensation nuclei and aerosol optical depth (AOD) above the tropical Indian Ocean. Aerosols are produced from strong winds and waves that lead to bubble bursting and sea spray emission [20]. Using AOD observations from two satellites, it was shown that sea spray aerosol is the dominant contributor to an increase in AOD. The sea spray aerosol flux depends on near surface wind speed, and thus soil gas carries aerosols into the atmosphere both over the land and over the sea. Consequently, their effect on the atmosphere and possible connection with electrodynamic processes in the surrounding space is similar. This is confirmed by the fact that the perturbation of the electric field is observed on satellites over EQs, the epicenters of which are located both on land and at sea.

Soil gases, the intensity of which increases on the eve of an EQ, carry charged soil aerosols into the atmosphere. Aerosols play such an important role in the Earth's radiation balance and climate change. These air suspended particles reflect or absorb sun lights and cause the change in measurement reflection from the surface by the sensor. Aerosol parameter can be obtained through various methods such as ground stations or using satellite images. One of the parameters which can be derived from satellite imagery is AOD, which is determined by measuring the absorption of light at specific wavelengths 550 nm of the visible spectrum. The aim of investigation is to reveal the possible changes of atmospheric AOD associated with EQs by using MODIS data from both Terra and Aqua satellites. Authors of [21] showed using the AOD data that a significant change can be seen seven days before the Wenchuan EQ occurred on 12 May 2008. They compared their results with other atmosphere and ionosphere anomalies, which were obtained by other studies. The result shows a clear enhancement of AOD along the Longmenshan faults 7 days before the quake, which is 1 day and 4 days earlier than the reported negative and positive ionospheric disturbances, respectively, and is 1 day earlier than or quasi-synchronism with other reported atmospheric anomalies including air temperature, outgoing long-wave radiation and relative humidity. The spatial distribution of AOD enhancement is very local and it is correlated well with the active faults and surface ruptures. There are extensive reports of ionospheric disturbances before the great 2008 Wenchuan EQ, which are possibly explained by seismogenic electric field hypotheses linked with the aerosols injected in the atmosphere. This unique enhancement could be associated with the LAI coupling process during the preparation of the Wenchuan EQ. Authors of [22] obtained aerosol parameters before and after the Gujarat EQ which took place on 26 January 2001. The data from Gujarat coast show significant changes after the EQ. The aerosol parameters have been deduced along the Gujarat coast and also along the profile from the coast to the remote ocean. Variation of aerosol parameters shows significant changes after Gujarat EQ. Correlation of aerosol injection into the atmosphere and other anomalies observed during the preparation of Chile EQ of 27 February

2010, is obtained in the paper [23], in which aerosol parameters were analyzed on the basis of AOD satellite data. The results of the analysis were compared with the data of anomalies registration of GPS-TEC, ions density, total ion density, electron density, electron temperature and VLF electric field. All of these anomalies and AOD data indicate a clear abnormal increase in time series several days prior to the event. Analyzing the time series of AOD for 16 strong EQs around the world, striking anomalies are seen before and after the EQs [24]. The rate of AOD increases due to the pre-seismic aerosols and gas injection in the atmosphere before the strong EQ. There is a significant change in AOD due to dusts also because of aftershocks after the EQ. This behavior suggests that there is a close relationship between EQ and the unusual AOD variations. An enhancement in number density of charged aerosols by one to two orders and the increase in atmosphere radioactivity in seismic areas due to the injection of radon and other radioactive substances were observed during days and weeks before an EQ [25] [26] [27] [28] [29]. Data on injection of the soil gases such as radon, helium, hydrogen, carbon dioxide in the seismic area ~500 km hours to few weeks before an EQ have been reported by [11]. Author of [30] presented the data on significant emissions of metallic aerosols Cu, Fe, Ni, Zn, Pb, Co, Cr and radon.

3. Penetration of an Electric Field into the Ionosphere

First, the seismic-related DC electric fields in the ionosphere had been observed by [31]. The observations were made onboard the Intercosmos-Bulgaria 1300 satellite at the altitudes ~800 km. The data show that the vertical DC electric fields of 3 - 7 mV/m were observed in the magnetically conjugate zones of the epicenter about 15 minutes before the EQ with magnitude $M = 4.8$ in the Pacific Ocean. It was argued in [31] that the observed fields were not of ionospheric or magnetospheric origin, but were associated with the EQ. Subsequent investigations of DC electric field in the ionosphere based on direct satellite measurements over seismic regions were carried out by [32] [33], 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 were observed over different tectonic structures at different latitudes. Statistical analyses of full package of available satellite data made in [32] [33] led them to the conclusion on the existence of seismic related electric field disturbances of the order of 10 mV/m in the ionosphere over the EQ zones both in land and in ocean. Let us give another example of the registration of a quasi-static field of seismic origin in the ionosphere. Authors of [34] presented new results after processing the data obtained by DEMETER satellite at the altitude (660 - 710) km. Typical perturbations were picked up in quasi-static electric field around some large EQs in 2010. And then, 27 EQs were selected to be analyzed on quasi-static electric field in two seismic regions of Indonesia and Chile at equatorial and middle latitude area respectively. Three-component electric field data re-

lated to EQs were collected along all the up-orbits (in local nighttime) in a limited distance of 2000 km to the epicenters during 9 days with 7 days before and 1 day after those cases, and totally 57 perturbations were found around them. All the results show that the magnitude of quasi-static electric field perturbations varies from 1.5 to 16 mV/m in the upper ionosphere. And the perturbations were mainly located just over the epicentral area or at the end of seismic faults. The quasi-static electric field observations on the Earth's surface in seismic regions were carried out by numerous researchers [35] [36] [37] [38]. Analyses of their publications show that the local electric field surges with large amplitude reaching few kV/m are observed during the EQ preparation, but the surge duration is of the order of ten minutes or less. However, no any significant DC electric field disturbances with duration of several days observed simultaneously over the horizontal distance of hundreds of kilometers have been reported. These long times and large-scale disturbances on the Earth's surface never exceed the background level ~ 100 V/m.

Along with seismic events, catastrophic meteorological phenomena in the lower atmosphere are accompanied by perturbations of the quasi-static electric field in the ionosphere. Response of the ionosphere and the upper atmosphere to intense meteorological processes was studied by [39] [40] who have made measurements of the electric field over active thunderstorm clouds. DC electric field exceeding 80 mV/m in magnitude were observed in the stratosphere at the distances ~ 100 km from thunderstorm cells. It was found that the vertical electric current density exceeded 120 pA/m² at the altitudes 50 - 60 km. First, the hurricane effects on the ionosphere were studied with use of the COSMOS-1809 satellite by [41] [42] who analyzed the data on DC electric field and plasma density disturbances obtained on the passages over tropical cyclone regions at the altitudes ~ 950 km. Direct measurements onboard the COSMOS-1809 satellite revealed localized DC electric field disturbances with magnitudes up to 25 mV/m and accompanying plasma density variations $\delta n/n \sim 6\%$ over the zones of strong atmospheric perturbations. According to ground measurements, the quasi-static electric field directly under powerful thunderstorms reaches values of the order (1 - 10) kV/m [43]. Summarizing the direct experimental data given above, we can formulate the basic properties of quasi-static electric field connected with powerful phenomena in the near-Earth space. An enhancement of seismic activity produces DC electric field disturbances in the ionosphere on the order of 10 mV/m. The similar effect is generated in the ionosphere by typhoons. Such disturbances occupy the region with horizontal scale of the order of (100 - 1000) km over the seismic region and the epicenter of typhoons. DC electric field enhancements occur in the ionosphere from hours to 10 days before an EQ. Long term (\sim several days) variations of the quasi-stationary electric field on the Earth's surface in a seismic area do not exceed the background value ~ 100 V/m while the same variations in a thunderstorm area can attain tens of kV/m. One of the most developed interpretations of these phenomena is based on the at-

mosphere-ionosphere coupling provided by the effects of DC electric field generation. These issues are discussed in detail in the reviews [44] [45].

Let us consider the processes which could be responsible for the generation of DC electric field in the atmosphere and the ionosphere. The local short-time releases of active substances and their accumulation in the lower atmosphere can generate the impulses of electric field near the Earth's surface, whose amplitude can reach tens kV/m with duration less than tens of minutes [46]. 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 near-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, the local pulses of the electric field are generated in the atmosphere. The amplitude of such a field is estimated as 10^3 to 3×10^3 V/m, and the relaxation time of an aerosol cloud is found to be ~ 10 minutes. The duration of such impulses is about 10 minutes, while the seismic related DC electric field in the ionosphere exists for a much longer time, up to days and weeks. The field occurs inside a dipole layer of charged aerosols cloud and slumps outside the layer. Consequently, the localized impulse electric field observed on the Earth's surface cannot produce any ionospheric effect and be a cause of quasi-static electric field appearance in the ionosphere prior to an EQ. A generation mechanism of electric field in the lithosphere based on the results of laboratory experiments has been proposed by [47]. Their experiments showed 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(positive)-holes. Positive electric potential, ionization of air molecules and corona discharge occur on the rock surface. This mechanism can be used to interpret the impulse phenomena due to very short (~ 10 min) operation time of the source, but not to explain the existence of DC electric field in the ionosphere over a much longer period of time.

Below we consider the generation mechanisms for DC electric fields in the ionosphere. This field has a horizontal scale 100 - 1000 km and the life time from a few hours to weeks. The field is quasi-static if its temporal variation exceeds considerably the relaxation time (τ) of charges in the atmosphere $\tau \sim \epsilon_0 / \sigma \sim (10 - 30)$ minutes (ϵ_0 is the electric constant, and σ is the near surface atmosphere conductivity). The current flowing in the circuit is excited by a generator, which denotes the resultant action of thunderstorms over the globe. The fair-weather current density is of the order of 10^{-12} A/m² in the closed circuit [43]. 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. 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 magnetosphere and ionosphere 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 modification of DC electric field in the ionosphere over a seismic region can be realized in two different ways. First is connected with any change of the load resistance and second—with the inclusion of an additional EMF (electro-motive force) in the global circuit.

Let us consider the first way. About 80% of load resistance in the global circuit is concentrated in the lower atmosphere, which is under the influence of EQ preparation processes. The injection of radioactive and chemical substances and aerosols into the atmosphere, the variation of aerosols sizes and the state of atmosphere result in a change of load resistance. Finally, all of these processes may change conductivity of the near ground atmosphere. For the first time, authors of [48] 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 investigated effects of the atmosphere ionization by alpha particles and gamma radiation of the nuclear decay and 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 enhancement of conductivity in the near-ground atmosphere. According to [49], the radon surge with magnitude 10 Bq/m^3 leads to an increase in ionization rate up to $(10^6 - 10^7) \text{ l/m}^3\text{s}$. As a result, conductivity of the near-earth atmosphere is increased by 1.5 times, and the field in the ionosphere is varied approximately by 1.5 times as well. As it was noted, 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. Authors of [50] have shown that an increase in ionization rate by radon in two times leads to a variation of the current flowing from the ionosphere to the Earth by 10%, and therefore the electric field variation in the ionosphere should be of the same value. Thereby, any model based on the assumption that the additional ionization of the lower atmosphere leads to the formation of seismic-related electric field in the ionosphere is in apparent contradiction with the experimental fact that the magnitude of DC electric field in the ionosphere is about 10 mV/m. So, a small variation of the field does not produce any change in the state of the ionosphere because the amplitude of variation is considerably smaller than the value of background variations.

In a number of works, calculations of the characteristics of the field in the ionosphere, based on a given value of the field on the Earth's surface are presented [51] [52]. The nature of electric field source on the Earth's surface and its characteristics are not discussed within their model. Electric fields in the ionosphere are computed for different boundary conditions, shape and size of field horizontal distribution on the Earth's surface. Calculations 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, 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 or two orders, the field value in the daytime ionosphere is approximately 10^{-3} mV/m. Thus, the considered model appears to be in contradiction with the well-known experimental data, which indicate an enhancement of pre-EQ DC electric field in the ionosphere over the epicenter zone up to 10 mV/m. So, we can conclude that no DC electric field of lithospheric origin exists in the ionosphere.

Let us consider the perturbation of a global electrical circuit by a current source located in the atmosphere. Calculation of the electric field in the ionosphere over thunderstorm clouds was carried out by [53]. However, there is a principal difference between the phenomenon of electric field penetration into the ionosphere during a thunderstorm and during EQ preparation. Namely, the quasi-static electric field near the Earth's surface under a thunderstorm cloud has a magnitude up to ($10^3 - 10^4$) V/m [43], while the near-ground electric field in EQ area does not exceed the background value ~ 100 V/m. This is why the above-mentioned method by in [53] did not allow us to elaborate the workable mechanism for DC electric field penetration from the EQ preparation zone to the ionosphere. Let us consider now a different way of DC electric field formation in the ionosphere. The basic point of this way is that the electric field and currents are varied due to the inclusion of a seismic-related EMF in the global circuit. The EMF can be located in the atmosphere and in the vicinity of boundary between the lithosphere and atmosphere. This way of modeling was started by [54] and then was actively developed (see the review [45] and references therein). Their model is based on the assumption that an additional current source in the circuit caused by the pre-EQ processes arises in the near-ground atmospheric layer. The EQ preparation processes modify the atmosphere in this layer and form an EMF over the seismic zone and the corresponding source of external electric current in the global circuit. Thus, the electric field observed on the Earth 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 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 fair-weather current, while the value of external current exceeds the fair-weather current by four to five orders. Therefore, the conductivity current in the ionosphere is of the order of external current of EMF near the surface. 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. This model allowed us 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.

4. The Reaction of the Ionosphere to the Penetration of an Electric Field

Large-scale irregularities of the ionosphere

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/GLONASS receivers network 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. Data from direct observations of seismic related quasi-static electric field in the ionosphere are confirmed by computational modeling of the ionospheric perturbations occurring at an eve of EQs.

The method for measuring TEC using GPS/GLONASS receivers has achieved significant progress lately. The TEC variation is defined by the plasma concentration change in the ionospheric F layer in the altitude interval (200 - 1000) km. The analyses of TEC spatial distribution have been carried out, for example, by [55] [56]. Their observations indicate that there are possible both the growth and depletion of TEC. Computation simulations show that observed TEC variations appear 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. It was further suggested that a general cause of TEC perturbation was vertical plasma drift in the zonal electric field. Authors of [57] have shown that the magnitude of the electric field disturbance is required to be 3 to 9 mV/m. One should keep in mind that appearance of the electric field in the ionosphere leads not only to plasma drift in the F layer. 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. 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. 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. 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. An increase in aerosols concentration near the Earth's surface by several times leads to a relative TEC variation of several tens of percent. The characte-

istics 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 [58].

Another mechanism of seismic-related TEC formation was considered by [59], who assumed that ionospheric density variations can be caused by Earth's surface charges/currents produced from electric currents associated with the stressed rock [47]. The stressed rock acts as a dynamo to offer currents for the global circuit. Their simulation results show that a current density $\sim(10^{-7} - 10^{-6})$ A/m² 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 $\sim(10^7 - 10^8)$ 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.

For the study of long-term ionosphere dynamics, we use special well-tested radio-physical methods. In some studies (e.g., [6] [60] [61]) the specific variations of the amplitude and phase of VLF transmitter 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 appear 3 - 10 days before an EQ. The characteristics of propagation of VLF/LF (LF (low frequency), 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 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 [61], who presented the proofs of existence of the ionosphere perturbations related to the EQs using a statistical analysis and separate case studies. Authors of [6] have shown that during a few days prior to the EQs there were anomalies in the form of decreases in the amplitude and phase of the signals. The spectra of perturbations were also analysed, 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. The growth of seismic-related quasi-static electric field in the ionosphere changes significantly the characteristics of AGWs as found by [62], who have shown that background AGWs 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 AGWs. 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 in [62], the 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. 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 [6].

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. Authors of [63] 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 [64]. High-altitude rocket measurements in the medium-latitude ionosphere showed that the electron number density in the sporadic layer was $2 \times 10^{11} \text{ m}^{-3}$, and the electric field in this layer reached 10 mV/m [65]. 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. The perturbation of electric current in the global circuit is caused by modification of the ionospheric E layer. Authors of [66] 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.

The data manifesting modification of the ionospheric *D* region over epicenters of future EQs was presented by [67]. In these papers anomalous effects were detected at observatories of the Schuman resonances (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 electromagnetic waves. Authors of [63] 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. Authors of [68] 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. Electric current perturbation in the global circuit by an additional EMF is accompanied by the ionospheric modification.

Small-scale ionospheric irregularities

The small-scale (4 - 10 km) fluctuations of plasma density $dN_e/N_e \approx 3\% - 8\%$ correlated with the increase in seismic-related ELF (extremely low frequency) emission intensity were registered [69], and the sizes of disturbed zones of plasma density dN_e and ELF waves occupy a latitude range ($3^\circ - 4.5^\circ$). 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 [70] on the basis of analyses of the first three events from COSMOS-1809 and of the data of AUREOL-3 satellites. Authors of [69] confirmed this result by two other events. The new result of this study is that the small-scale plasma irregularities $dN_e/N_e \sim 3\% - 8\%$ 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 emissions were detected simultaneously. These results are confirmed by recent satellite DEMETER data [71], which revealed ULF (ultra-low frequency) 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 [72]. The analyses of satellite data revealed the electric field disturbances up to 15 mV/m in the ionosphere over a typhoon region [41] [42]. 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. Despite the fact that the sources of generation of the quasi-static field in the ionosphere are different, the processes of formation of inhomogeneities are quite similar.

Generation mechanism of plasma irregularities caused by DC electric field amplification in the ionosphere was suggested by [73]. This mechanism is based on the instability of AGWs, forming horizontal inhomogeneities of electrical conductivity, magnetic field-aligned currents and related plasma density irregularities stretched along geomagnetic field lines. Irregularities of such a kind were observed earlier in the ionosphere over EQ preparation zone [69]. The growth of electric field in the ionosphere leads to an instability of AGWs [73]. 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. 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. Estimation shows that the value of critical field is (6 - 10) mV/m. 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 [74]. For the electric field greater than the threshold value, there are generated the dipole vortex structures in the ionosphere. 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. Transverse spatial scale of the layers coincides with the scale of conductivity irregularities. Authors of [73] made an estimation of the relative changes of plasma density in the layer elongated along the magnetic field $\Delta N/N_0 \approx (1.6 - 16)\%$ and of the transverse spatial scale of irregularities $l \approx 4 - 40$ km. 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. 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 [75]. Authors of [76] also demonstrated the effects of plasma and field-aligned current filamentation due to strong plasma density gradients in the high-latitude ionosphere. Thus, one can expect two characteristic spatial scales for seismic-related ionospheric disturbances: 4 - 40 km and ~ 100 m across the magnetic field.

5. Electromagnetic Phenomena

Authors of [7] [77] 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. 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 [78] [79], 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. Authors of [80] 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. 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.

The results of ELF/VLF measurements on board the satellite COSMOS - 1809 in the Spitak EQ region have shown [69] that the intensity of ELF radiation is ~ 10 pT at a frequency of 140 Hz and ~ 3 pT at a frequency of 450 Hz. Authors of [81] 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 [82]. According to a generation mechanism of electromagnetic ELF precursors to EQs [83], 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. The lowest eigenmode of sub-ionospheric waveguide (TM (transverse magnetic) mode) exhibits the weakest attenuation at frequencies below 1 kHz and can therefore propagate over large distances. 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 inhomogeneities are observed. Authors of [84] [85] 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.

The existence of seismic related electric field in the atmosphere is indirectly confirmed by the observational data on the generation and propagation of VHF electromagnetic emissions. Anomalous VHF emissions in two frequency bands around 41 and 53 MHz were detected on the eve of EQs whose epicenters were located both on land and at sea [86]. The signals were observed on the Earth's surface behind the horizon line at a distance of ~ 300 km from the epicenter. Their registration is possible only if the radiation source is located in the atmosphere above the earth's surface. Based on the obtained data, Ruzhin and Nomicos (2007) [87] have shown that the source of radiation in the VHF band associated with the preparation of EQs is located in the lower atmosphere at altitudes from 1 to 10 km above the epicenter of the future EQ. The analysis of VHF transmitter signals over the horizon was also carried out by [88] [89], and significant growth in the signal amplitude is observed if the propagation path is located over the seismic region. Authors of [88] 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. Authors of [5] [90] have additionally observed the anomalous VHF-band radio-wave propagation beyond the line of sight prior to EQs.

Authors of [91] have proposed a generation mechanism of atmospheric disturbances resulting from changes in geochemical quantities associated with EQs and VHF radio wave refraction. It has been shown [92] 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. Calculations of the spectrum of electromagnetic radiation behind the horizon from the epicenter of seismic region are derived. The electric current of random discharges is found to excite electromagnetic radiation in the range of 10 - 100 MHz with amplitude of the order of 6 $\mu\text{V/m}$. 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 [93], which are caused by disturbances of electric current in the global atmosphere-ionosphere circuit. 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. The scattered field is propagated over the horizon with respect to the transmitter. Based on the elaborated theory the spatial distribution of mean value of scattered wave electric field over the horizon has been calculated. The radiation amplitude increases significantly during EQ preparation if its epicenter is located in the vicinity of signal propagation path. 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.

One can consider that the electric discharges in the troposphere may be a source of other phenomena; the glow of discharges region and the atmospheric heating of the disturbed region [94]. 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 density 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 $3 \times (10^{-3}$ - $10^{-2})$ 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 oc-

currence 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 on the atmosphere and ionosphere. Based on the radar data, authors of [95] 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 [96]. Author of [97] 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 [98]. 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 [99]. Outgoing long wave radiation can be generated by the ozone emission [100] 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 [101].

6. Conclusions

Both regions of atmosphere and ionosphere are a united environment, in which the physical phenomena are related to each other. Intensive processes in the lithosphere and lower atmosphere give rise to electro-dynamical influence onto the ionospheric plasma. Among them are impending EQs, volcanic eruption, typhoons, thunderstorms, anthropogenic disasters. According to the 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. 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 several orders of the field magnitude in the ionosphere in comparison with experimental data.

A principally different model is based on the assumption that the current sources in the circuit connected with pre-EQ processes are situated in the near-ground atmospheric layer. The EQ preparation processes modify the atmosphere in this layer and form an EMF in the seismic zone. 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. A fundamentally different physical idea is implemented in the electrodynamic model of electromagnetic and plasma precursors to EQs. The most important is that this model allows us to explain the results of observation of quasi-static electric field both in the ionosphere and on the Earth's surface in seismic regions, because other models could not explain the nature of such a field. In the frame of this model they found the mechanism for increase of conductivity electric current with altitude and the mechanism for limitation of vertical component of the electric field near the ground. The increase mechanism is realized by a decrease with altitude of EMF external current while maintaining the total current, which is the sum of conductivity and external currents. The EMF external current is formed in the near ground atmosphere. 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 near ground electric field is limited by a feedback mechanism between the EMF external current and the electric field generated in the atmosphere over a seismic source. In one sense the above-mentioned model is similar to the model of AGW influencing 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 together with 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 EMF electric current can affect the ionosphere simultaneously, though the consequences of these effects can be different. 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.

According to the electrodynamic model, the growth of electric field in the ionosphere is caused by the EMF formation and the related variations of elec-

tro-physical characteristics of lower atmosphere as a result of the injection of soil gases, aerosols and radioactive substances in a process of EQ preparation. It was shown that the appearance of EMF in the global electric circuit leads to the stimulation of a set of plasma and electromagnetic phenomena observed in experiments. An enhancement of the electric field might result in the instability of AGWs in the ionosphere. This process is accompanied by the generation of field-aligned currents and plasma irregularities stretched along the magnetic field lines in the upper ionosphere. Their appearance leads to ULF magnetic field oscillations and spectral broadening of ground-based VLF transmitter signals as observed on satellites crossing the disturbed magnetic field tube over the seismic area. 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 and the generation of GWs propagated along E layer of the ionosphere. The presence of seismic related irregularities in the lower ionosphere provides the formation of the line spectra of ULF oscillations and the change in resonance frequency of SRs. One more effect of the appearance of irregularities in the nighttime ionosphere is the depressions of ULF magnetic pulsations of magnetosphere origin observed on the ground. The growth of electric field up to the breakdown value and the formation of random electric discharges might generate VHF radio emission in the troposphere over EQ epicenter. The generation of conductivity current in the global electric circuit is accompanied by the ionosphere modification. Large scale perturbations in D region of the ionosphere may be generated by both the transfer of charged particles and electron heating. The layer with high 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 into the ionosphere results in the growth of plasma density in the E region and the formation of sporadic layer. Modification of F region and growth of light ions density are caused by heat release due to the electric current flow in the E region of ionosphere. The spatial TEC distribution arises as a result of the ionosphere heating and the plasma drift, with the TEC behavior depending on the relationship between them. The results of studies of these processes are discussed in detail in the reviews and monographs [10] [44] [45] [102] and works referenced therein.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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