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Electrodynamic Model of Ionospheric Precursors of Earthquakes and Certain Types of Disasters

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Abstract—The model presented is the result of the theoretical studies of electromagnetic and plasma precursors of earthquakes. According to this model, slow variations in the parameters of the lower atmosphere above a seismic zone initiate short-period disturbances of the ionospheric plasma and electromagnetic field. These effects are mainly caused by the vertical turbulent transfer of charged aerosols and radioactive matters injected into the atmosphere. This results in the formation of the vertical external current and horizontal inhomogeneities of the ionospheric conductivity. Field-aligned currents and plasma inhomogeneities in the upper ionosphere, which are ducts of whistler modes and are registered on a satellite as ULF oscillations of the geomagnetic field and electron density fluctuations, are formed as a result of their interaction with the electric field. The interaction between the conductivity irregularities and the background electromagnetic radiation results in ELF emissions in the ionosphere and ULF oscillations on the Earth's surface.

1. INTRODUCTION

Seismic activity of the Earth is continuously controlled by the global network of seismic stations recording all underground shocks. The epicenter position and hypocenter depth, orientation of the Earth's crust plane of displacement, movement direction, etc. are determined. Seismic zoning is performed as a result of such measurements; i.e., a possible seismic hazard is determined for each region. Earthquakes mostly occur at the boundaries of the Earth's crust blocks, and the velocity of movement along a fault and the deformations in source zones are increased before an earthquake. Therefore, geodynamic measurements of the Earth's crust zones make it possible to localize faults and epicentral regions of future earthquakes and to make a long-term prediction of seismic activity. However, by the present, traditional methods for seismic control do not make it possible to timely predict earthquakes, i.e., to obtain a warning several days and hours before an event. Along with geodynamic effects in the Earth's crust, intense geodynamic and chemical effects of a seismic center on the atmosphere and ionosphere accompany seismic activity. Numerous anomalies of fields and parameters of the near-Earth space appear several days and hours before a main shock as a result of such an effect. In this case the ionosphere is a sensitive pickup controlling earthquake preparation dynamics. Therefore, much attention has recently been paid to studying ionospheric precursors of earthquakes.

2. MAIN RESULTS OF STUDYING ELECTROMAGNETIC AND PLASMA PRECURSORS OF EARTHQUAKES

Numerous recent studies convincingly indicate that the relation exists between processes in the Earth's lithosphere and disturbances in the atmosphere and ionosphere. It has been shown that numerous anomalous changes in parameters of the medium and the electromagnetic field occur during the earthquake preparation phase and at its different stages [Buchachenko *et al.*, 1996; Liperovsky *et al.*, 1992]. An analysis of satellite data indicated the presence of electromagnetic disturbances in the wide spectral range, localized in the magnetic field tube connected to an impending earthquake source. Electromagnetic emission bursts in the frequency band (1–10^4) Hz recorded in the ionosphere [Chmyrev *et al.*, 1989; Gokhberg *et al.*, 1982; Serebryakova *et al.*, 1992] and simultaneous registrations of emissions in the same frequency band on the satellite and in the seismic zone [Koons and Roeder, 1999] are presented. The relation of these processes to the earthquake preparation has been indicated. The reliability of electromagnetic emissions in the ionosphere induced by earthquakes has been corroborated by the statistical studies based on large bodies of satellite data obtained for tens and hundreds of earthquakes [Parrot, 1999]. The disturbance of the DC electric field in the ionosphere and on the Earth's surface is recorded [Chmyrev *et al.*, 1989; Gokhberg *et al.*, 1988; Tate and Daily, 1989]. The origination of up to 10%-fluctuations of electron density with periods of 1 Hz is observed [Chmyrev *et al.*, 1997]. These results have been corroborated by the statistical studies of electron density disturbances in the ionosphere based on the large body of satellite data [Afonin *et al.*, 1999]. Changes in the ion composition and plasma temperature in the topside ionosphere and disturbances of the latitude profile of the ionospheric *F* region are recorded [Boskova *et al.*, 1994; Pulinets *et al.*, 1994; Wollcot *et al.*, 1984]. An analysis of the bank of satellite images of the Earth's surface in the IR band indicated the presence of stable and unstable components of the anomalous IR radiation flux over active faults, corresponding to the increase in the temperature of the near-Earth atmosphere by several degrees [Gornyi *et al.*, 1988; Qiand *et al.*, 1999; Tronin, 1999]. Tens of works include not only data on electromagnetic disturbances in the ULF band and 0.1–10 Hz geomagnetic pulsations recorded on the Earth's surface before earthquakes but also a detailed analysis of signals and detection of their different indications related to characteristics of an incipient earthquake. We mention only several recent works. Alperovich and Zheludev [1999] presented data on the ULF emission intensification in the seismic region observed from 5 h to 2 days before the earthquake. They indicated that the oscillations propagate over the Earth's surface at a velocity dependent on their period, which shows that the disturbances are of the ionospheric origin. Similar disturbances in the ULF band, related to lithospheric sources in the focus of the incipient earthquake were studied by Fraser-Smith *et al.* [1990], Hayakawa *et al.* [1996], and Troyan *et al.* [1999]. The modification of the characteristics of whistlers observed on the Earth's surface has been found [Hayakawa *et al.*, 1993; Oike and Ogawa, 1982], and the relation between the earthquake preparation processes and electric field disturbances has been established [Hao, 1988]. Moreover, the increase in seismic activity is related to the anomalous airglow in the 557.7 and 630 nm lines [Fishkova, 1985; Toroshelidze and Fishkova, 1986] and disturbances of the ionospheric *E* and *F* regions [Davies and Baker, 1965; Gufel'd, *et al.*, 1994; Pulinets *et al.*, 1998] and ULF and HF radiosignals on routes crossing the zone of earthquakes [Fuks and Shubova, 1994; Nestorov, 1979; Ralchovsky and Komarov, 1988]. An analysis of the disturbance of the ULF signal with a frequency of 10.2 kHz, propagating over a seismic zone, indicated that the ionosphere oscillation amplitude starts growing a week before the earthquake at an altitude of 70–90 km with a period of 5–10 days [Molchanov, 1993]. At the same time, the concentration of some gases (e.g., H_2, CO_2, and CH_4) increases by orders of magnitude, the level of atmospheric radioactivity (caused by such radioactive elements as radon, radium, uranium, thorium, and actinium and products of their decay) becomes higher, and the injection of soil aerosols increases [Alekseev and Alekseeva, 1992; Heincke *et al.*, 1995; Virk and Singh, 1994; Voitov and Dobrovol'skii, 1994]. Optical phenomena in the form of lightning flashes and glows [Papadopoulos, 1999] and radioemission pulses with a frequency of 22.4 MHz [Maeda, 1999] are observed immediately before earthquakes in the atmosphere over the seismic region.

The above effects were observed onboard spacecraft or with the help of ground-based equipment several hours or weeks before earthquakes, depending on their type; therefore, they can be considered as earthquake precursors. A joint analysis of observations makes it possible to conclude that an earthquake preparation is accompanied by an intensification of different processes in the near-Earth atmosphere and by a formation of sources in the lower atmosphere, which stimulate numerous plasma and electromagnetic effects in the ionosphere. Recently, the nature of seismic–ionospheric interactions has become more comprehensible due to intensely developing theoretical studies and creation of physical models of disturbance transfer from a seismic center into the Earth's atmosphere and ionosphere. Observations indicate that the Earth's surface vibrations, chemically active and radioactive substances, and electrically charged aerosols simultaneously affect the lower atmosphere on the eve of an earthquake. The lower atmosphere warms up, its electrophysical parameters sharply change, acoustic waves are generated, and vertical external currents are formed as a result of this effect. An acoustic effect on the ionosphere is realized as a result of the upward propagation of infrasonic and acoustic gravity waves. Theoretical studies are largely devoted to a search for mechanisms explaining a specific experimental fact. The formation of the ULF emission on the Earth's surface due to lithospheric sources [Molchanov, 1999; Surkov and Pilipenko, 1999] and the possibility of its penetration into the ionosphere [Molchanov *et al.*, 1995] have been considered. The modification of the ionosphere altitude profile is related to the plasma drift during the electric field enhancement [Kim and Hegai, 1999]. The possibility of the action of infrasonic waves on the ionosphere is discussed [Liperovsky *et al.*, 1997]. It is assumed that internal gravity waves (IGW) are generated, propagate upward, and disturb the ionosphere as a result of the processes in the lower atmosphere (long-period oscillations of the Earth, heating of the atmosphere, and injection of gases) [Gokhberg *et al.*, 1996]. Similar works draw up numerous chains of processes between sources and measured parameters. Another approach to studying earthquake precursors consists in a joint analysis of a set of possible parameters observed. This analysis can be physically based on a model that makes it possible to interpret most of satellite and ground-based observations as a manifestation of one cause. In this case measured parameters proved to be interrelated by certain regularities. Such an approach has been realized in the electrodynamic model of the atmosphere–ionosphere coupling, whose main statements are presented below.

3. ELECTRIC FIELD ENHANCEMENT IN THE IONOSPHERE

An electrodynamic effect on the ionosphere is realized as a result of a change in the electric current in the global electric circuit, some part of which is occupied by the current flowing from the ionosphere toward the Earth [Sorokin and Yashchenko, 1999, 2000a, 2000b; Sorokin *et al.*, 2001]. The current value in the circuit changes during a generation of the vertical external current and at a change in the resistivity of the Earth–ionosphere layer. The electrical load of the atmospheric current circuit is mainly concentrated in the lower atmosphere, whose conductivity is governed by ionization sources (chemical, electrical, and radioactive) and by a mobility of ions. Radioactive elements come into the atmosphere together with soil air. An increase in the level of atmospheric radioactivity during earthquake preparation results in an increased ion production rate and electrical conductivity of the lower atmosphere. Different mechanisms of external current generation in the near-Earth atmosphere are possible before an earthquake. An intensified ejection of charged soil aerosols into the atmosphere or a change in meteorological conditions at their stable altitude distribution can be one of such mechanisms. A quasistationary vertical distribution of aerosols is formed as a result of the upward eddy transport and gravitational sink. Turbulent vortices carry charged aerosols and related external current from altitudes where their concentrations are high to altitudes with low concentration of aerosols. The appearance of external vertical currents in the lower atmosphere is equivalent to the connection of EMF to the atmosphere–ionosphere electric circuit. In this case the current in the circuit and, correspondingly, the electric field (E_0) are changed. The disturbed electric field (E) in the Earth–ionosphere layer, caused by the generation of the external current (j_s) in the near-Earth atmosphere, is determined from the following equality [Sorokin *et al.*, 2001] in a quasistationary approximation, when this current changes with a characteristic time exceeding $1/4\pi\sigma_0$:

$$E(z,t) = -E_0(z,t) - \frac{1}{\sigma(z)}\left\{ j_s(z,t) - \frac{\int_0^h j_s(z,t)\frac{dz}{\sigma(z)}}{\int_0^h \frac{dz}{\sigma(z)}} \right\},$$

$$E_0(z,t) = \frac{U}{\sigma(z)\int_0^h \frac{dz}{\sigma(z)}},$$

where h is the altitude of the lower ionosphere, σ is the atmospheric conductivity, and $U = \varphi(h) - \varphi(0)$ is the potential drop between the ionosphere and the Earth. To estimate the electric field value in the ionosphere, let us consider the case when the external current changes with altitude slower than conductivity. In this case we can factor the altitude variation in the external current in the last summand outside the integral, having replaced it by the value at the integrand maximum:

$$\int_0^h j_s(z)\frac{dz}{\sigma(z)} \approx \bar{j}_s(0)\int_0^h \frac{dz}{\sigma(z)},$$

where $\bar{j}_s(0)$ is the average value of the external current near the Earth's surface. In this case we obtain that

$$E(z) = -E_0(z) - \frac{j_s(z) - \bar{j}_s(0)}{\sigma(z)}.$$

On the Earth's surface $j_s(0) \approx \bar{j}_s(0)$; therefore, $E(0) \approx -E_0(0)$. Let us estimate the electric field value in the ionosphere. For $z = h$, we obtain:

$$E(h) = -E_0(h) - \frac{j_s(h) - \bar{j}_s(0)}{\sigma(h)} \approx -E_0(h) + \frac{\bar{j}_s(0)}{\sigma(h)}$$

$$= -E_0(h) + \frac{\bar{j}_s(0)}{j_0}E_0(h),$$

$$E_0(h) = E_0(0)\frac{\sigma(0)}{\sigma(h)}.$$

We estimate the first summand in this equality. Assuming that the value of the undisturbed field on the Earth's surface is $E_0(0) = 150$ V/m and the conductivity values are $\sigma(0) = 2 \times 10^{-14}$ S/m and $\sigma(h = 80 \text{ km}) = 10^{-6}$ S/m, we obtain that $E_0(h) = 3 \times 10^{-3}$ mV/m. The second summand differs from the first one by the ratio of the values of the external current near the Earth's surface and the undisturbed atmospheric current $j_0 = 3 \times 10^{-12}$ A/m^2 = 8.7×10^{-7} cgse. The external current value will be estimated from the formula $\bar{j}_s(0) = 4\pi\sigma(0)qH_j(N_+ - N_-)$. Taking the following values of the parameters $\sigma(0) = 2 \times 10^{-14}$ S/m $= 2 \times 10^{-14}$ cgse, $q = e = 4.8 \times 10^{-10}$ cgse, $H_j = 2$ km $= 2 \times 10^5$ cm, $N_+ = 4 \times 10^3$ cm^{-3}, and $N_- = 0$, we obtain: $\bar{j}_s(0) = 8.7 \times 10^{-4}$ cgse $= 3 \times 10^{-9}$ A/m^2 = $10^3 j_0$. Consequently, $E(h) \approx \frac{\bar{j}_s(0)}{j_0}E_0(h) = 3$ mV/m. Thus, if the external current propagates to an altitude exceeding the vertical scale of the atmospheric conductivity, the ionospheric field increases by several orders of magnitude due to the $\bar{j}_s(0)/j_0$ factor. The external current can move upward as a result of the vertical convection of the atmosphere during heating of its near-Earth layer. The atmosphere becomes unstable and the vertical convection begins, if the absolute value of the temperature (T) vertical gradient exceeds the critical value $dT/dz = -g/c_p$, approximately equal to 1° per 100 m. According to satellite data [Qiang *et al.*, 1999], the increase in seismic activity is accompanied by heating of the lower atmosphere by several degrees. This heating can be related to the greenhouse effect, Joule heating at the appearance of external currents, etc. The other factor of ionospheric field enhancement operates concurrently with the upward flow of the external current. This is an increased conductivity of the lower atmosphere due to, e.g., an increased level of atmospheric radioactivity and a decreased conductivity of the ionosphere, which can be caused by the upper transfer of hydrogen molecules. The joint action of the above processes results in the enhancement of the ionospheric electric field to several–tens mV/m. This is corroborated by the satellite records of the 8-mV/m ionospheric electric field above the zone of the incipient earthquake (Fig. 1) [Chmyrev *et al.*, 1989]. Similar results have recently been obtained by Isaev *et al.* [2000], who observed electric field disturbances of 20–30 mV/m in the ionosphere over the regions of typhoon passage, where a similar mechanism of generation of the external current is realized (see Fig. 1). The plasma and electromagnetic effects accompanying the enhancement of the ionospheric electric field are presented below.

4. GENERATION OF FIELD-ALIGNED CURRENTS AND PLASMA INHOMOGENEITIES

The electric field enhancement in the ionosphere results in the instability of acoustic gravity waves (AGW) [Chmyrev *et al.*, 1999; Sorokin and Chmyrev, 1999; Sorokin *et al.*, 1998]. This instability is related to the transformation of the Joule heating of ionospheric currents into a wave energy. The propagation of insignificant acoustic oscillations in this medium is accompanied by the disturbance of conductivity and, consequently, currents. Under certain conditions, these disturbances are so considerable that the Joule heating of disturbed currents results in a growth of the AGW amplitude. EMF of the external electric field is the energy source for this instability. Thus, under the action of the external electric field, an AGW instability results in a increased disturbance of plasma density and in the formation of horizontal irregularities of the ionospheric conductivity.

Horizontal irregularities of the conductivity change the ionospheric electric fields and form plasma sheets along the magnetic field [Chmyrev *et al.*, 1999; Sorokin and Chmyrev, 1999; Sorokin *et al.*, 1998]. High conductivity along magnetic field lines results in the electric field propagation into the upper ionosphere and magnetosphere, which is accompanied by the generation of field-aligned currents and local changes in plasma density. Thus, the appearance of the horizontal spatial structure of the ionospheric conductivity results in the formation of plasma sheets extended along the geomagnetic field. The transverse spatial dimensions of these sheets coincide with the scales of the conductivity horizontal spatial structure. When a satellite crosses plasma inhomogeneities, it simultaneously registers plasma density fluctuations [Chmyrev *et al.*, 1997] and geomagnetic pulsations with the same period [Chmyrev *et al.*, 1989], since these inhomogeneities are formed by field-aligned currents. The scheme of registration is shown in Fig. 2.

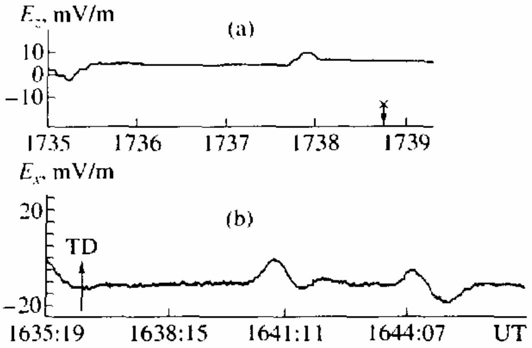

Fig. 1. Examples of observations of the DC electric field disturbance in the ionosphere over the zones of (a) incipient earthquake [Chmyrev *et al.*, 1989] and (b) tropical storm [Sorokin *et al.*, 2001].

5. FORMATION OF WHISTLER DUCTS IN THE UPPER IONOSPHERE

Small-scale plasma structures, originating as a result of AGW instability under the action of the electric field, play a role of waveguides or ducts, channeling whistler modes along the Earth's outer magnetic field [Sorokin *et al.*, 2000]. Ducts represent plasma inhomogeneities (extended along the geomagnetic field) with a transverse spatial scale of about 10 km and with a plasma density change of about 10% relative to the background value. As a result of the appearance of such structures in the ionosphere over an epicentral zone, magnetospheric whistlers come into the Earth–ionosphere waveguide with a higher probability and dispersion characteristics of signals received on the Earth's surface are changed in this zone. Hayakawa *et al.* [1993] found out the effect of seismic activity on a propagation of magnetospheric whistlers. Using a statistical analysis, they determined that the characteristics of the whistler anomalous propagation at low latitudes (such as increased dispersion and occurrence frequency) are caused by seismic activity. These researchers discussed possible mechanisms of such an effect. Specifically, they assumed that seismic activity affects the entrapment of whistlers by the waveguide or results in the formation of a waveguide. This idea was experimentally corroborated [Chmyrev *et al.*, 1997] by the satellite observations of small-scale inhomogeneities of plasma density (see Fig. 2). Let us indicate the characteristic manifestations of this model [Sorokin *et al.*, 2000] that can be found during the registration of whistlers: (1) the multi-beam (fine) structure of whis-

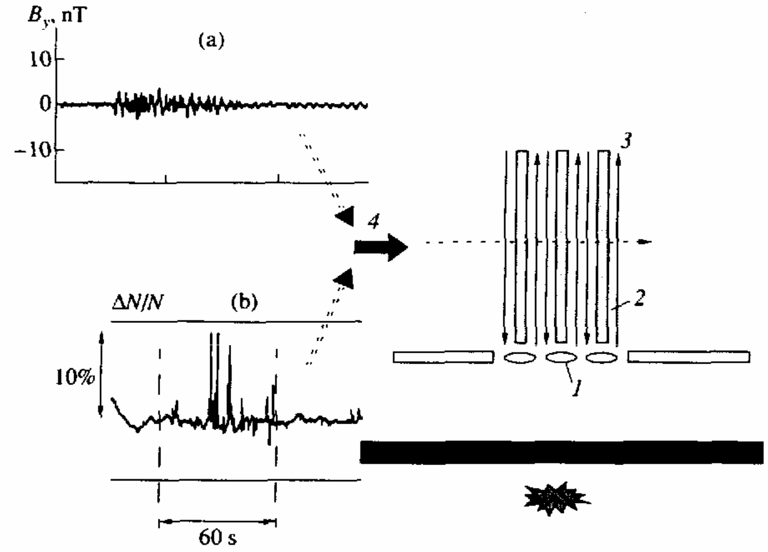

Fig. 2. The scheme of the satellite observations of (a) plasma density inhomogeneities [Chmyrev *et al.*, 1997] and (b) ULF oscillations of the geomagnetic field [Chmyrev *et al.*, 1989]: (*1*) horizontal irregularities of the ionospheric conductivity; (*2*) plasma density inhomogeneities extended along the geomagnetic field; (*3*) field-aligned currents; (*4*) satellite.

tlers related to the structure of distributed plasma inhomogeneities generated by AGW; (2) the correlation of anomalous whistlers with the enhancement of the electric field and plasma density fluctuations during simultaneous ground-based and satellite observations; and (3) the formation of the structure of field-aligned currents and related ULF magnetic pulsations in the ionospheric region magnetically conjugate to an earthquake focus.

6. EMISSION OF ELF ELECTROMAGNETIC WAVES INTO THE UPPER IONOSPHERE

As was mentioned above, satellite data indicating that the ELF electromagnetic emission increases on the eve of earthquakes were presented in many works. Certain mechanisms of generation of such signals have been discussed for the last several years [Liperovsky *et al.*, 1992; Molchanov *et al.*, 1993]. The calculations performed indicated that, for frequencies of about several hundred hertz, these mechanisms result in the much less significant effects than it was observed experimentally. Borisov *et al.* [2001] presented the new mechanism of whistler mode emission in the upper ionosphere. These modes were generated as a result of the transformation of pulsed ELF noise on the small-scale conductivity irregularities in the lower ionosphere. As was mentioned in Section 4, these irregularities are caused by the AGW instability during the electric field enhancement over the seismic region. ELF electromagnetic pulses are generated by lightning discharges and propagate in the subionospheric waveguide with low absorption. The lowest eigenmode of the subionospheric waveguide (the so-called TM-mode) has the lowest absorption at frequencies below 1 kHz and, consequently, can propagate over long distances. The electric field of this mode is directed vertically as a result of the high conductivity of the Earth's surface layer. The electric field horizontal component appears with increasing altitude. Its value approaches the vertical component amplitude in the spectral range 100–1000 Hz at altitudes of 115–120 km where the ionospheric conductivity is maximal. The horizontal component of the electric field generates polarization currents, dependent on wave frequency, on conductivity irregularities. These currents acts as sources of ELF waves propagating into the upper ionosphere and magnetosphere along magnetic field lines. The spectral intensity of the electric (E) and magnetic (B) fields of the ELF emission in the upper ionosphere is determined by the equality [Borisov *et al.*, 2001]:

$$|E|^2 = \left(\frac{4\pi}{c}\right)^2 \frac{\omega\omega_e}{\omega_p^2}[(E_x^0)^2 + (E_y^0)^2][(\Delta\Sigma_p)^2 + (\Delta\Sigma_H)^2],$$

$$B = nE,$$

where $n = \omega_p/(\omega\omega_e)^{1/2}$ is the refractive index of a whistler mode, $\omega_p = (4\pi e^2 N/m)^{1/2}$ is the plasma frequency, and $\omega_e = eB_0/mc$ is the electron gyrofrequency. It follows from this expression that the emission intensity depends on frequency, since the horizontal components of the electric field in the ionosphere and the refractive index of whistler modes depend on frequency. Results obtained agree with satellite observations shown in Fig. 3.

7. FORMATION OF ULF GEOMAGNETIC PULSATIONS ON THE EARTH'S SURFACE

According to observational data considered above, ULF electromagnetic oscillations of a noise character are increased near an incipient earthquake epicenter. Along with the lithospheric sources in the impending earthquake focus, [Troyan *et al.*, 1999], certain processes form the source of ULF oscillations, observed on the Earth's surface, in the lower ionosphere over the seismic zone [Alperovich and Zheludev, 1999]. The mechanism of their formation is based on the generation of gyrotropic waves (GW) in the lower ionosphere by the noise electromagnetic field in the presence of horizontal irregularities of the ionospheric conductivity, which are related to the AGW instability caused by the electric field enhancement [Sorokin *et al.*, 2000, 2001]. These waves propagate in the thin layer of the lower ionosphere along the Earth's surface at low an middle latitudes, being slightly attenuated and having phase velocities of tens–hundreds km/s [Sorokin, 1986, 1988; Sorokin and Fedorovich, 1982]. Different electromagnetic emission sources generate electromagnetic noise in the band of ULF and geomagnetic pulsations. Polarization currents, which are the sources of GW, are generated under the action of this noise in the region of horizontal inhomogeneities of the ionospheric conductivity (see Fig. 4). The appearance of such quasi-coherent sources with a horizontal spatial scale of 10 km results in the formation of narrow-band geomagnetic oscillations on the Earth's surface with a characteristic frequency of several fractions of unity to several hertz. The relative spectrum of oscillations $|B_{x1}(x, \omega)/B_{x0}(\omega)|$, formed by the relative disturbance of the Hall conductivity $\sigma_{H1}(x)/\sigma_{H0} = m\exp(-|x|/L)\cos k_0 x$, is determined from the expression [Sorokin *et al.*, 2000, 2001]:

$$\frac{B_{x1}(x, \omega)}{B_{x0}(\omega)} = -m\left(\frac{\omega}{\Omega}\right)^2$$

$$\times\left\{\frac{e^{-|x|/L}\sin k_0|x|}{1+qL} + \frac{i}{1+(qL)^2}\exp[i(k_0+q)|x|]\right\},$$

where $\Omega = \sqrt{L/\omega_0 u}$; $\omega_0^2(k) = 2la^2|k|^3$; $u = d\omega_0(k_0)/dk_0$; $q = (\omega^2 - \omega_0^2 + i\nu\omega k_0^2)/2\omega_0 u$:

$$\nu = \frac{c^2\int_{-\infty}^{\infty}\sigma_{P0}(z)dz}{4\pi\int_{-\infty}^{\infty}\sigma_{H0}^2 dz}; \quad a = \frac{c^2}{4\pi\left[l\int_{-\infty}^{\infty}\sigma_{H0}^2 dz\right]^{1/2}};$$

$$l = \int_{-\infty}^{\infty}\sigma_{H0}^2(z)dz/\sigma_0^2.$$

Figure 4 indicates the spectrum of geomagnetic oscillations, calculated from this formula for different epicenter distances from the region with horizontal scale L, which includes conductivity irregularities with amplitude m and horizontal wavelength $2\pi/k_0$. The spectrum

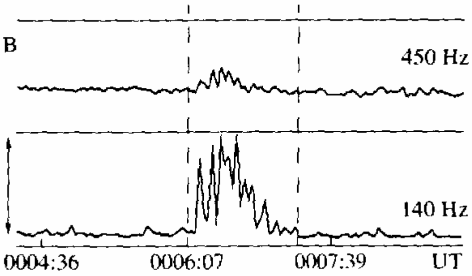

Fig. 3. An example of ELF emissions observed on the satellite above the zone of incipient earthquake [Chmyrev *et al.*, 1997].

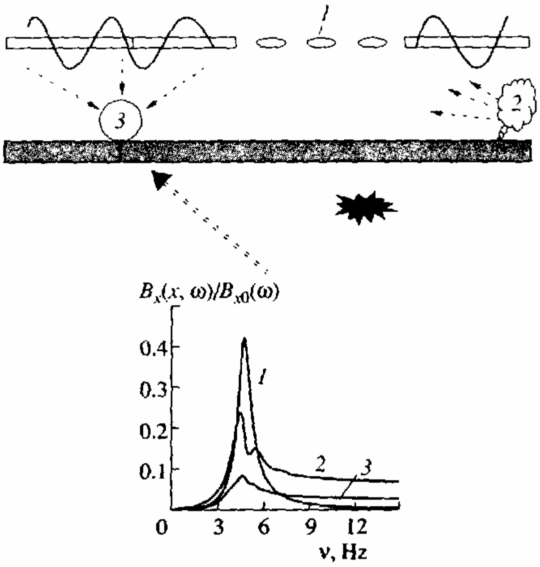

Fig. 4. The scheme of formation of the geomagnetic field ULF oscillations on the Earth's surface: (*1*) horizontal irregularities of the ionospheric conductivity; (*2*) sources of the electromagnetic background emission; (*3*) registration point. (a) Results of calculating geomagnetic field ULF oscillations at different distances from a seismic zone epicenter: (*1*) $x = 0$, (*2*) $x = 100$ km, and (*3*) $x = 200$ km.

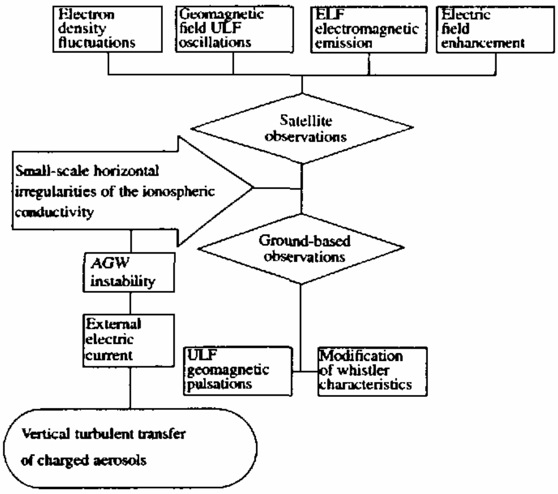

Fig. 5. The scheme of the processes forming the electrodynamic model of the effect of seismic and meteorological phenomena on the ionosphere.

maximum frequencies account for several hertz and decrease with increasing spatial scale of irregularities.

8. MODIFICATION OF THE IONOSPHERE VERTICAL PROFILE

The contribution of the Joule heating of the ionospheric currents in the zone of earthquake preparation to the total thermal balance of the ionosphere is substantial. Therefore, the effect of this thermal source on the state of the ionosphere is decisive. Heating by ionospheric currents increases scales of the vertical distribution of the ionospheric components and, consequently, the $F2$ layer altitude profile. This mechanism, along with other possible mechanisms, should contribute to the observed response of the ionosphere to the processes of earthquake preparation [Sorokin and Chmyrev, 1999].

9. CONCLUSIONS

The electrodynamic model presented relates a number of quantities recorded onboard the satellites and on the Earth's surface to the increase in the DC electric field [Sorokin and Chmyrev, 1999; Sorokin *et al.*, 1998, 2001]. Its enhancement depends on the change in the current in the ionosphere–Earth circuit, which is related to the intensification of the ionization, electrophysical, chemical, and meteorological processes in the lower atmosphere during the increase in seismic activity on the eve of earthquakes. The scheme of the plasma and electromagnetic effects originating as a result of the electric field enhancement is shown in Fig. 5. According to this model, electric field enhancement is accompanied by the origination of:

(1) AGW instability and horizontal irregularities of the ionospheric conductivity;

(2) field-aligned electric currents and plasma inhomogeneities oriented along the geomagnetic field;

(3) whistler ducts in the upper ionosphere and magnetosphere;

(4) electromagnetic ELF emissions in the upper ionosphere and magnetosphere;

(5) geomagnetic ULF oscillations on the Earth's surface;

(6) convective processes and a change in the ion composition.

The model indicates that these effects are interrelated by a common cause, and their registration makes it possible to control an intensification of the processes in the lower atmosphere caused by large-scale catastrophic phenomena. This work is not a review of results of studying ionospheric precursors of earthquakes; therefore, other physical mechanisms, which, along with the model presented, make their own contributions to the electromagnetic and plasma effects observed during preparation of earthquakes, are not discussed here.

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