On recent physical models of lithosphere-atmosphere-ionosphere coupling before earthquakes

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On recent physical models of lithosphere-atmosphere-ionosphere coupling before earthquakes

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Abstract. In the present work, an attempt is made to explain and to evaluate the most interesting and physically important models of lithosphere-atmosphere-ionosphere coupling before earthquakes. In some of the models it is assumed that in the near-Earth atmosphere above the region of earthquake preparation atmospheric acoustic and acoustic-gravity waves are excited and propagate through the atmosphere up into ionospheric altitudes, where they cause electric field disturbances and changes of the density of the charged particles. Other models suggest that ionospheric disturbances are the consequence of modifications of electric fields and currents which are caused by electric processes of the lithosphere or near-Earth atmosphere. It is unpossible to consider only one of the explained models and to neglect all the other models as the characteristic spatial scales of the observed ionospheric phenomena before earthquakes lie between 200-300 km and a few thousands of kilometres, and the characteristic temporal scales are in the interval between some minutes and a few days. One may conclude that the real lithosphere-ionosphere coupling is the result of the action of some different physical mechanisms.

1 Introduction

Recently, it is very actual and important to investigate physical processes accompanying different phases of earthquake preparation and to develop methods of earthquake prediction. Thus many experimental and theoretical works were performed, and it seems that science made an essential step into the direction of a possible solution of the problem of earthquake prediction. To the most essential and interesting results, obtained during the last two decades by radiophysical observations, there belong above all electromagnetic and ionospheric disturbances occurring before and during seismic activities.

For the first time, modifications of ionospheric parameters were mentioned by Davies and Baker (1964) in connection with the extremely strong earthquake in Alaska in 1964. This finding stimulated the search for earthquake precursors in the ionosphere. Ionospheric phenomena which were caused by the seismic eruption and by the propagation of the seismic waves after the eruption were frequently registered. Besides, various rarely and incidentally found effects were considered.

The observation of "anomalous" pulses of electromagnetic emissions in the frequency interval between a few Hz and some tens of kHz as well as the changes of the density of the charged particles registered by satellites were a stimulus for the further experimental investigation of the lithosphere-ionosphere coupling [Gokhberg et al. 1982, 1983; Migulin et al 1982, Larkina et al. 1983]. For the physical understanding of the processes in the system lithosphere-atmosphere-ionosphere, such works were of special importance, which were dedicated to the notification of disturbances of the atmospheric electric field [Gokhberg et al. 1988a], to "anomalous" geomagnetic pulsations [Gogatishvili 1984, Fraser-Smith et al. 1990], and "anomalous" disturbances in the ionosphere [Kolokolov et al. 1992] and the magnetosphere [Serebryakova et al. 1992, Parrot 1994]. Thereat also the connection between ionospheric disturbances and the discrete structure of the Earth's core (radio emissions above fracture regions of the Earth) [Shaftan et al. 1986] at seismic quiet times was mentioned.

One has to underline that since about 1980, and up to now, the number of publications concerning the coupling in the system lithosphere-atmosphere-ionosphere connected to earthquakes has been increasing every year. Recently, some hundred articles come out the year. The most full lists of references is given in the books by Gokhberg et al. (1988b), Liperovsky et al. (1992) and Pulinets and Boyarchuk (2004). According to an article by Pulinets [2006], ionospheric effects of earthquakes are studied in 20 countries, and alone in Russia there work on the topic 10 groups of scientists.

Nearly the whole research work, performed up to now in the field of lithosphere-atmosphere-ionosphere coupling related to earthquakes, had the aim to identify ionospheric precursors of earthquakes and to solve the problem of short-time earthquake prediction. To find solutions was more complicated than supposed. It turned out that the earthquake precursors possess difficult temporal and spatial structures, that the maximum effects are not always obtainable directly above the epicenter, and the amplitude of the precursor does not always increase when the time approaches the moment of the earthquake. Correspondingly, it became necessary to develop adequate physical models to interprete the lithosphere-atmosphere-ionosphere coupling.

In the present work, a series of - according to the viewpoint of the authors - basic experimental results and most interesting physical models of lithosphere-ionosphere coupling some days before earthquakes are reviewed. Phenomena connected to earthquakes, which occur after the seismic eruptions, are of less interest. First, in the article some important experimental results demonstrating the lithosphere-atmosphere-ionosphere links are analysed. Then an attempt is made to explain and to discuss the most interesting physical models proposed up to now to describe these links. It has to be mentioned that up to now no generally accepted models exist.

2 Some most important experimental results

The observation of disturbances of a series of characteristic parameters of the ionosphere before earthquakes is of principal importance for the understanding of the possible perspective of earthquake predictions by satellites. Such satellite experiments essentially accelerated the investigation of seismo-ionospheric earthquake precursors. In the following, some examples are given.

Searching for possible seismo-ionospheric effects, during the analysis of data obtained before earthquakes by the satellite "Interkosmos-19" at F-region altitudes an increase of both the intensity of VLF noise with frequencies between 140 Hz and 15 kHz and the disturbances of the electron density at distances from the epicentres up to a few 1000 km were found for the first time in [Migulin et al. 1982, Gokhberg et al. 1982, 1983, Larkina et al. 1983]. In 1981, during the analysis of the distribution of the electron density in the upper part of the F2-layer registered by "Interkosmos-19" [Pulinets and Boyarchuk 2004] it was concluded that about one day before an earthquake the altitude of the maximum of the electron density of the F2-layer increased from about 280 km to about 360 km, but the maximum of the electron density decreased from $3 \cdot 10^5$ cm^{-3} to 10^5 cm^{-3}. This phenomenon was very estonishing, and it stimulated the further search for ionospheric and magnetospheric precursors of earthquakes.

Registering variations of both the components of the magnetic field in the frequency region of 0.1-8 Hz and the vertical component of the quasi-constant electric field by the satellite IK-B1300, before the earthquake with the magnitude $M = 4.8$ on January 2, 1982, pulses of the vertical quasi-static electric field of 3-7 mV/m were observed twice, at a distance of 2000 km from the epicentre about 15 min before the earthquake and directly above the epicenter about 12 min before the event. The regions where the effect was observed had a latitudinal dimension of about 1.0 grad -1.5 grad, and the amplitude of the observed magnetic pulsations amounted to 3 nT at a frequency of about 1 Hz [Sorokin et al. 1998].

During the registration of the variations of the plasma density and the ELF/VLF noises by "KOSMOS-1809" near Spitak, some days-hours before the eruption, intensive magnetic disturbances were found in a region of $\pm 6^o$ in longitude and $\pm 4^o$ in latitude with respect to the epicentre of the preparing earthquake (that means at distances of up to 500 km from the epicentre). There the amplitude of the magnetic disturbances rose up to about 10 nT at a frequency of 140 Hz, and up to about 3 nT at 450 Hz. In the same region where the anomalous ELF magnetic disturbances were excited, also small-scale (4-10 km along the orbit) inhomogeneities of the plasma density of $\Delta N/N_o \approx 3 - 8$ % were observed. Besides sudden temperature changes and density decreases were found (see e.g. [Sorokin et al. 1998]).

During the newest studies of earthquake preparation phenomena using data registered by the satellite DEMETER, one found a damping of VLF radiosignals by external sources at F-region altitudes at distances of 1000-5000 km from the earthquake epicentres about 0-3 weeks before the event [Molchanov et al. 2006].

Thus by satellite experiments, episodes of spikes of low-frequency plasma turbulence, and regions of increased temperature and decreased density in the upper part of the F-layer above seismo-active zones at distances up to 1000 km from the epicentre are obtained. Because of such distances, the observations were of less interest for the solution of the prognose problem, but they remained important for the understanding of the physical mechanisms. Besides there do not exist statistical proves of the effects found by satellites. These phenomena were rarely obtained - and only during tenths of seconds during the satellite flights above seismo-active regions.

2.1 Lithosphere-ionosphere phenomena in the F-layer

A rather large part of statistically reliable - or almost statistically reliable - seismo-ionospheric effects is found by ionospheric sounding experiments. A special analysis of the investigations of the ionosphere before earthquakes showed, that specific kinds of anomalous ionograms before earthquakes practically do not occur. For a long time, scientists have been looking especially for such ionograms, but they did not find them. Thus, investigating ionospheric effects during times of earthquake preparation, it became necessary to show the main laws of the temporal behaviour of some ionospheric parameters statistically. It had been suggested that the modifications in the ionosphere caused by processes of earthquake preparation are rather weak. And, not to take into account direct solar influences, usually, first only the night-time ionosphere was studied.

Of course, during the investigation of the seismo-ionospheric effects, there arose questions about their characteristic time scales and length scales. The time scales were found to be in the interval from a few minutes to some hours, and the length scales were shown to be between a few hundreds and a few thousands of kilometres [Liperovsky et al. 2002, Meister et al. 2002]. The large interval of characteristic time scales of lithospheric-ionospheric effects expresses the complexity of a series of physical mechanisms - and not of a single mechanism - happening during the time of earthquake preparation. Up to now it is not yet finally clear, which mechanisms belong to this complex of processes.

Investigating seismo-ionospheric effects of the F-layer, it was found that the maximum ionization density growths about 3-7 days before earthquakes, and then it decreases. The minimum was obtained 0-2 days before the event [Pulinets and Boyarchuk 2004, Korsunova and Hegai 2005, Liu et al. 2006]. The mentioned phenomena were registered by vertical sounding stations at distances of 500-1000 km from the epicentres.

About 0-2 days before the earthquakes also the turbulization of the F-layer weakens [Liperovskaya et al. 2006], which is to be seen as decrease of the F-spread and of the variability of the maximum ionization density with characteristic time scales of 2-3 hours [Popov et al. 2004]. On the other hand, the variability of the ionization density below the electron density maximum of the F-layer, at altitudes of 200-250 km, increases. The spatial scales of these effects are up to 500 km [Liperovsky et al. 1992].

Recently ionospheric phenomena related to earthquakes are obtained by satellites using GPS. There one studies the total electron content in a vertical air columne between Earth surface and altitude of satellite observation. The electrons of the F-layer mainly contribute to the total electron content. In the works by Pulinets et al. [2004] and Liu et al. [2004], it was shown using GPS, that about 1-7 days before strong earthquakes the variability of the total electron content grows, provided that the point of the observation lies in the earthquake preparation region.

2.2 Lithosphere-ionosphere phenomena in the E-layer

At altitudes of the ionospheric E-layer at night, the regular electron density amounts to $10^2 - 10^3$ cm^{-3}, which is below the working level of the ionosonde. Thus, one usually studies sporadic E-layers the density of which is 2-3 orders of magnitude larger. The formation of sporadic layers is believed to be connected with the wind-shear effect. If the direction of the horizontal wind in the E-layer changes its direction by 180 deg. and the vertical gradient of the wind reaches values of 0.05-0.06 s^{-1}, then the charged particles are accelerated into the direction to the point with vanishing velocity value (more exactly, into the direction of the zero value of the divergency of the wind velocity). As a result, a sporadic E-layer forms. The destruction of sporadic E-layers is mainly caused by ambipolar and turbulent diffusion.

The maximum electron density in sporadic E-layers amounts to $10^5 - 10^6$ cm^{-3}, and their horizontal dimensions vary between 10 and 100 kilometres. The vertical thickness of the sporadic layers changes between some hundreds of meters and some kilometres. Often sporadic layers possess an inhomogeneous horizontal structure - spots and isles of ionization. And they have also vertical inhomogeneities - the Es-spread.

Studying the dynamics of sporadic layers using ionosondes, one can measure the modifications of the maximum ionization density of the layer and the characteristics of the inhomogeneity or the turbulization of the layer. The large-scale turbulization (hundreds of meters) may be observed by the E-spread effect - the diffusivity of the traces of the layers in the ionograms. The small-scale (tenths of meters) turbulization is characterized by the coefficient of the semi-transparency of the layer.

During the investigation of the ionospheric phenomena it was shown statistically, that one day before an earthquake the maximum electron density decreases, but two days before the event, the number of modifications of the density with characteristic time scales of 15 minutes very often increases. The large-scale turbulence (E-spread) is strengthened, but the small-scale turbulence occurs more rarely. This phenomenon is observed for earthquakes with magnitudes $M > 5$. The spatial dimensions of the mentioned phenomena amount up to 300-500 km [Alimov et al. 1989, Liperovskaya et al. 1994a, Liperovskaya 2006].

But in the E-layer also effects with scales of 500-1000 km were found. Especially, it was shown that the correlation coefficient of sporadic layers above vertical sounding stations, which are situated at a distance of some hundreds of kilometres, decreases 1-2 days before earthquakes, if the epicentre of the earthquake is located at distances $\leq$1000 km from the sounding stations [Liperovsky et al. 2002].

The mentioned experimental results may be interpreted assuming that in the ionosphere some processes compete. The observations show that before earthquakes in the ionosphere acoustic and acoustic-gravity waves (AGWs) with periods between parts of minutes and hours propagate, that electric fields and currents are excited, and that heating processes occur. The main experimental results are listed in Table 1.

3 Lithosphere-atmosphere-ionosphere coupling models

Now, the physical coupling mechanisms in the system lithosphere-atmosphere-ionosphere at seismic activity will be reviewed.

3.1 Acoustic-gravity models

The acoustic-gravity hypothesis (AGH) is nowadays one of the most popular hypotheses. According to it, some days before the eruption, in the region of earthquake preparation near the Earth's surface atmospheric acoustic-gravity waves (AGWs) are excited, which propagate through the atmosphere and reach ionospheric altitudes. Further, the disturbances of the neutral component of the ionosphere, due to

Table1. Ionospheric precursors of earthquakes (experiment)

altitude	method	parameter	anomaly	distance (km)	time before earthquakes
above F-layer	satellite	0.11-8 Hz (VLF-noise)	$\uparrow \times 10 - 10^3$	1000	hours
	satellite	140 Hz - 15 kHz	$\uparrow \times 10 - 10^3$	longitude: 1000, latitude: 6000	hours-days
F-layer	ion-sound	F-spread	$\uparrow$ 10 %	500	days
	ion-sound	density disturbances	$\uparrow \times 2, \tau = 2$ h	500	days
	photometer	630 nm	$\uparrow 15 - 40\%$	1000	days
Es-layer	ion-sound	density	$\downarrow$ 10 %	500	hours-days
	ion-sound	strong density disturbances at the layer boundaries	$\uparrow$ 10 %	500	days
	ion-sound	E-spread	$\uparrow$ 20%	300	days
	photometer	557.7 nm	$\uparrow$ 7%	200	hours
D-layer	SDW	disturbances of the signal phase	$\uparrow$	1000	hours-days

the collisions of the neutral particles with the ions, cause disturbances of the density of the charged particles of the ionosphere [Mareev et al. 2002, Gokhberg and Shalimov 2004].

3.1.1 Rayghleigh-Taylor instability by AGWs at larger distances from the epicentres

In the work by Shalimov and Gokhberg [1998], using numerical models, it was shown that atmospheric AGWs which are excited in the near-Earth atmosphere a few days before earthquakes may propagate upward until altitudes of 120-150 km. Thereat the transfer of disturbances into the ionosphere proceeds in many steps. It is assumed, that the atmospheric AGWs are generated by non-stationary fluxes of gases from the lithosphere into the atmosphere. The waves then propagates up to ionospheric altitudes and may cause ionospheric plasma bubbles. Thereat the AGWs cause only the initial plasma disturbances which then give the reason for the plasma Rayghleight-Taylor instability which is connected with of orders larger energies. The investigation of the effectivity of the possible generation mechanisms of AGWs showed, that the obviously most effective generation is caused by the non-stationary gas flux [Perzev and Shalimov 1996] (energy flux of the order of 0.1 erg/(cm^{2}s)). The influence of the processes of earthquake preparation on the F-layer may be obtained at distances up to a few 1000 km. Such an influence may be only explained by the AGW mechanism, and the waves should have rather large characteristic time scales. It should be mentioned that earthquake preparation processes do not only influence the F-layer, but also the ionospheric E-layer at distances of up to 1000 km from the epicentre [Liperovskaya et al. 1994]. A possible mechanism which might cause the formation or destruction of sporadic E-layers at such distances - this is only such a mechanism where AGWs play the main role. We underline at this place, that the generation process of the AGWs is not yet sufficiently studied experimentally up to now.

3.1.2 AGW action at smaller distances from the epicentres because of seismic mosaic-like structure

Another group of scientists [Mareev et al. 2002, Molchanov 2004] considered AGWs of smaller periods of some minutes and up to tenths of minutes. With these AGWs one may explain the existence of ionospheric phenomena at smaller distances from the epicentres. The authors considered a mosaic structure of the sources of AGWs of seismic origin. Such sources, formed by chaotic inhomogeneities, may be much more effective AGW generators than sources which are homogeneously distributed in space. In the works, the region of earthquake preparation was modeled as a mosaic source of heat and mass having a characteristic time scale of the order of or larger than the Brünt-Väissälä period of the atmosphere. With other words, waves with structures were assumed, and for the explanation of the ionospheric phenomena the mosaic structure of the disturbances was of importance.

In accordance to [Molchanov 2004], the Kolmogorov turbulence in the ionosphere is the result of the evolution of the AGWs, and the time of transfer of the disturbances from the Earth's surface to the ionosphere amounts to some hours and depends on the wave period.

Consequently, the both mentioned acoustic-gravity hypotheses may explain observations of ionospheric disturbances before earthquakes, which may be obtained by ionosondes and by satellites, especially at distances from the epicentre which are of the order of or larger than 1000 km.

3.1.3 AGW sources

Now the reasons for the AGW occurrence in the near-Earth atmosphere will be discussed in detail. It is known that during seismic measurements the spectrum of seismo-gravity oscillations of the Earth with periods between 30 min and 4 h are usually registered [Lin'kov et al. 1989, 1990]. Besides, observations also showed that long-periodic oscillations with periods in the interval of 1-5 h may be excited a few days before strong earthquakes with magnitudes $M \geq 6.0$ [Garmash et al. 1989]. The intensification of such oscillations obviously occurs, for instance, in the modulation of the intensity of the natural electromagnetic emissions (NEE) and of the F-layer disturbances in the interval of periods of $t = 2 - 3$ h before earthquakes [Liperovsky et al 1992, Bella et al. 1992, Popov et al. 2004].

The generation of AGWs (with periods of some minutes and up to some hours, whereat waves with periods larger than one hour considered in the reviewed works are often called inner gravity waves) in the seismo-active region may be caused by different reasons. Such reasons are the motion of the Earth's core which possesses a block-like structure, unstable thermal anomalies caused by the outflux of greenhouse gases into the atmosphere in fracture regions of the Earth's core, but also the unstable outflow of masses of lithospheric gases into the atmosphere [Gokhberg et al. 1996]. During seismo-gravity oscillations, the Earth's surface may act on the atmosphere like a stopper. Thereat variations of temperature, conductivity and pressure are generated and cause themselves the excitation of AGWs in the atmosphere. Besides, on the compressional phase, these oscillations may lead to an outflow of radon and other gases into the atmosphere.

On the basis of meteorological observations in Middle Asia short-time meteorological earthquake precursors were detected - anomalous variations of atmospheric pressure, relative humidity, air temperature and wind velocity [Mil'kis 1986]. Such anomalous variations were observed some hours-days before some earthquakes. It was suggested, that the reasons of the pressure variations were temperature variations of the Earth's surface on large areas. One may suppose that the generation of AGWs may be also caused by meteorological reasons.

It should be mentioned, that in winter and autumn about two days before earthquakes on ionograms sufficiently often the appearance and disappearance of traces of weak sporadic layers with characteristic time scales of 30-60 min are observed. In such cases, a larger variability is usually found at distances up to 500 km from the epicentre, which is in accordance with the effective propagation distances of AGWs with periods of 30-60 min.

The obtained growing intensity of the air-glow at night (at a wave length of $\lambda = 5577\mathring{A}$) may also be interpreted within an acoustic-gravity model. At wave dissipation on the non-linear stage of their propagation, due to turbulent vertical mixing of the neutral atmosphere, the concentration of NO^+, the temperature of the E-layer, and consequently, the intensity of the air-glow increase.

One may assume that simultaneous observations of pressure and other meteorological parameters in seismo-active regions within a network of stations on the Earth's surface, together with the ionospheric observations, would allow to confirm experimentally the here presented hypotheses of lithosphere-atmosphere-ionosphere connections. But such experiments are rather difficult, and up to now nobody has them carried out. The main observations which are interpreted basing on the proposed hypothesis are listed in Table 2.

Table 2: Acoustic-gravity wave (AGW) hypothesis of lithosphere-atmosphere-ionosphere connections at large horizontal scales. The distance from the epicentre amounts to 500-2000 km.

Observation of VLF pulses by satellites which are caused by plasma instabilities at AGW dissipation	upper ionosphere $H > 700$ km
1. Change of the wind system in the E-layer, destruction of the correlations of the density of sporadic layers registered by different vertical sounding stations 2. Increase of the temperature in the D- and E-layers, growth of the turbulent mixing, increase of the number of NO^+ in the D-layer, change of the phase of the SDW-signal	D- and E-regions of the ionosphere
Pressure modifications and excitation of AGWs with a period of $T > (10 - 15)$ min. outflow of gases out of the Earth's surface, change of the surface temperature	atmosphere
compressional processes and shifts in the Earth's core, excitation of seismo-gravity waves	Earth

3.2 Models considering the modification of the atmospheric electric field

Now models will be considered which explain small-scale and short-time electrical processes at rather small distances from the epicentres of the earthquakes.

3.2.1 Lithospheric-ionospheric coupling by radioactivity and electrical conductivity increase

According to the hypothesis of lithospheric-ionospheric connections which bases on the increase of radioactivity and electrical conductivity, in the near-Earth atmosphere the "quasi-constant electrical field is modified" [Pulinets et al. 1997, Sorokin 1998, Sorokin and Chmyrev 1998].

It is well known that the radioactivity of the atmospheric layers is mainly caused by radioactive elements like radon, radium, torium, actinium and their decomposition products. Radioactive elements get into the atmosphere together with the air of the ground. Together with the air flow, they propagate up to altitudes of some kilometres. Thereat the velocity of the ion-formation amounts to a few tenths of pairs of ions per cubic centimetre and per second. The results of the observations show an increase of the amount of radioactive material in the atmosphere before earthquakes. Consequently also the speed of ion formation and the electrical conductivity raised up [Pulinets et al. 1997].

For instance, the measurements of the radon concentration at a distance of 300 km from the epicentre of the earthquake on 20.10.91 on the north of India [Virk and Singh 1994] showed, that an intensive pulse of high radon concentration occurred about one week before the earthquake. The concentration of radon in the air grew about 2.5 times, and in the water it raised up by more than 1.5 times. In another case [Heinicke et al. 1995], the radon concentration grew about four times in the five pre-earthquake days. A statistical analysis taking into account 300 earthquakes showed that in about 70% of the cases the radon concentration grew essentially before the events.

3.2.2 Modifications of the "quasi-constant electric field"

In the works [Sorokin and Chmyrev 1997, 1998, Sorokin et al. 1998], a one-dimensional model of the modification of the "quasi-constant electric field" in the ionosphere by a local increase of radioactivity and, correspondingly, degree of ionization of the atmosphere, was proposed. Using this model, it is possible to interprete qualitatively the enhancement of the density of charged particles in the D- and E-layers of the ionosphere basing on the phenomenon of the increase of the electrical conductivity in the lower atmosphere in a sufficiently large horizontal area.

It has to be underlined that basing on the hypothesis of quasi-constant charges and electric fields, it is necessary to propose that the characteristic time scale of the modifications of the electric field originating in the lithosphere τ is much larger than the Maxwellian relaxation time $\tau_o = \varepsilon_o/\sigma_o \approx$ 15 min. Such a suggestion is, of course, linked with the supposition of a stationary working electric generator which, at the surface, would produce the same amount of charged particles as propagates up into the atmosphere. Here it has to be mentioned that according to [Imyanitov and Shifrin 1962, Chalmers 1967] the Earth-ionosphere system possesses an analogy to a spherical capacitor, where the potential difference between its clouds is determined by the thunderstorm activity.

The analysis of the experimental data formed the basis of the theoretical investigations resulting in the formulation of the hypothesis of the connection between lithosphere and ionosphere [Sorokin et al. 1998, Sorokin and Chmyrev 1997, 1998] during the modification of the quasi-constant electric field by the increase of the local radioactivity.

According to the model, the altitudinal distribution of the electrical conductivity and the electric field in the region between Earth and ionosphere is modified. If the radioactivity grows near the Earth's surface then also the electrical conductivity increases in a near-Earth atmospheric layer of a width of some kilometres, and the vertical electric field is changed. Near the Earth's surface, the strength of the electric field decreases because of the growing electrical conductivity, but at larger altitudes it increases in comparison with the undisturbed state. The electric field near the lower boundary of the ionosphere may raise up a few times. Thus, as the lower atmosphere is additionally ionized before earthquakes, the local electric field increases and changes in the ionosphere.

Under the action of the atmospheric electric field, an electric current directed to the Earth's surface is created. In the earthquake preparation region, during the compressional phase of the seismo-gravity waves, which are excited before the eruptions [Lin'kov et al. 1989, 1990], a radon outflow into the atmosphere may occur. The radon concentration may increase several times. The characteristic time scale of this process may amount to one or a few hours. With the increase of the radiactivity at the Earth's surface also the degreee of ionization and the electrical conductivity in the near-earth layer of the atmosphere of a few kilometres increase.

The intensity of the vertical electric field decreases. At large altitudes, the intensity of the electric field is larger than at seismic quiet times. The electric field near the lower boundary of the ionosphere may increase by some 100 %, and as a consequence, the Joule heating and the electron temperature in the E-layer grow. As a result, the ionospheric plasma moves locally and there are formed ionospheric inhomogeneities. This phenomenon is then related to the occurrence of ULF-ELF magnetic variations.

Here it has to be mentioned that the temperature increase in the E-layer causes a decrease of the recombination coefficient. Thus it is possible to interprete the local increase of the density of the charged particles in this ionospheric region.

3.2.3 Dissipative instability of AGWs

Another consequence of the disturbance of the electric field in the conducting region of the lower atmosphere is the dissipative instability of AGWs with a period near the Brünt-Väissälä frequency of about 5 min [Chmyrev et al. 1999]. The physical mechanism of the dissipative instability of the AGWs is related to an additional Joule heating by the disturbed currents during the modification of the ionospheric electrical conductivity in the wave. In the E-layer, the vertical electrical current changes accordingly, an inhomogeneous Joule heating occurs, the dissipative instability develops and horizontal periodic density inhomogeneities appear. The neutral component of the air starts to oscillate with the same period, field-aligned currents are generated, and moving layers of field-aligned currents and plasma densities are formed.

Horizontal variations of the conductivity with scales of $l = \lambda/2 = \pi V_g/\omega_g = \pi a/\omega_g n(\omega_g)$ (λ - wavelength) change the ionospheric electric field. The high conductivity along the magnetic field lines causes the propagation of the disturbances of the electric field into the upper layers of the ionosphere and magnetosphere. The thus appearing electrical circuit consists of field-aligned currents which transfer the electric field along the magnetic field lines, and of perpendicular currents which are brought about by the Pedersen conductivity. Thereat, the field-aligned currents are transferred by the electrons, but the transversal currents are caused by the ion motion. The closing currents are accompanied with local variations of the plasma concentration. Thus, the appearance of a horizontal structure of the electrical conductivity of the ionosphere gives reason to the formation of currents along the geomagnetic field. The perpendicular scales of the current layers coincide with the scales of the horizontal structure of the conductivity.

This physical mechanism may be applied for the explanation of satellite observations. When a satellite moves with a velocity V_s through a plasma inhomogeneity of horizontal scale l, then the registered disturbances of the plasma density and of the magnetic field possess time scales $\tau = l/V_s$. By satellites flying through the ionosphere, magnetic field disturbances with scales of the order of $\tau \approx 10^{-5}$ s are observed. According to quantitative estimates one has to do with relative density changes of the plasma of $\Delta N/N_o \approx 1.6 \pm 16$ %, amplitudes of the magnetic field of $\Delta B \approx 5$ nT, and a time interval during which the satellite crosses the field-aligned current and the plasma inhomogeneity of about $\Delta t \approx 0.3 - 3$ s [Serebryakova et al. 1992, Sorokin et al 1998, Chmyrev et al. 1998].

3.2.4 Quasi-elecrostatic model

One of the latest models of lithosphere-atmosphere-ionosphere coupling is the "quasi-electrostatic" one. This model also bases on the outflow of radon into the near-Earth atmosphere above fracture regions before earthquakes [Pulinets et al. 1998, 2000, 2006, Pulinets and Boyarchuk 2004, Pulinets and Lui 2004]. The authors tried to explain observations of the vertical electric field of the Earth of up to 10^3 V/m and of an increase of the radon concentration near the Earth's surface at earthquake preparation times. In the model, it is suggested that radon causes an additional ionization and the formation of negatively and positively charged ions. Thus, near the Earth's surface positively and negatively charged ions, and because of processes of hydratation, more complicated complexes of ions (ion clusters) occur. The ions are trapped by aerosols, and thus one finds a system of aerosols with charges of different signs within a layer with a thickness of about one metre. In the lower part of the layer, there are mainly positively charged particles, and in the upper part one has above all negatively charged ones. The process of charge separation proceeds under the action of the gravity force, so that the large particles, which are mainly negatively charged fall down, and the smaller, mainly negatively charged particles, are situated at larger altitudes [Frenkel' 1949]. Consequently, strong gradients of the atmospheric electric field within a near-Earth layer with a thickness of some metres occur.

The electric field above the layer increases the mean quasi-stationary electric field, and the vector of this field shows to the Earth's surface. The effectivity of the process of charge separation is determined by the intensity of the source of ionization. The model interprets preearthquake phenomena in the atmosphere and ionosphere as consequences of the occurrence of a vertical electostatic field with an intensity of some kV/m at the Earth's surface. As result of numerical calculations it was found, that the field "penetrates" even into ionospheric altitudes of 1000 km under quasi-stationary conditions. The obtained theoretical results are in agreement with experimental observations.

Table 3. Hypothesis of lithosphere-ionosphere coupling based on the consideration of the increase of radioactivity and electrical conductivity as well as on the modification of the quasi-constant electrical field in the near-Earth layer.

propagation of acoustic-gravity waves transfer of disturbances of the electro-magnetic field along magnetic field lines excitation of VLF oscillations of the magnetic field	upper ionosphere and F-region
increase of the vertical current, Joule heating, development of the dissipative instability, formation of horizontal periodic density inhomogeneities	E-layer
generation of acoustic-gravity oscillations with periods near the Brünt-Väissälä one (5 min.), occurrence of field-aligned currents	ionosphere
radon outflow, increase of atmospheric electrical conductivity, increase of the vertical current	atmosphere
shifts and compressions in the Earth's core	

3.3 Acoustico-electric model

The "acoustico-electric" hypothesis of the formation of an Es-generator and of small-scale currents under the action of acoustic pulses propagating up from the Earth's surface - this is one of the last hypotheses which is not yet sufficiently proven experimentally [Liperovsky et al. 1997, 2000]. According to this hypothesis which explains ionospheric phenomena at sufficiently near distances of a few hundred kilometres from the earthquake epicentres, it is suggested that pulses of neutral winds with time scales of some minutes exist.

In the cited works, it was shown that during the action of the neutral winds on a sporadic layer of finite horizontal dimensions at altitudes between 95 km and 130 km at night, the sporadic layer acts as non-stationary current generator. It was assumed that the winds at E-region altitudes may be caused by acoustic disturbances which are generated by earthquake preparation processes and propagate from the lower atmosphere into the E-layer within parts of minutes or within some minutes. Further, a three-dimensional system of electric fields and currents forms. The electric fields and currents, if certain conditions are satisfied, may be the reason of plasma instabilities and plasma turbulence. In [Liperovsky et al. 1997, 2000] presenting the model, it was assumed that the sporadic layers are situated in an environment of lower plasma density. It has to be mentioned that the acoustic disturbances propagating from the Earth's surface up into the atmosphere can reach ionospheric altitudes and influence the ionosphere only under the condition that their periods are in the interval between 1 min and 5 min [Blanc 1985]. By the dissipation of the infrasound emitted from the earthquake epicentre some hours before the eruption, according to the hypothesis, also variations of the air glowing are possible [Fishkova 1983].

Further, basing on the experimentally verified fact that a system of two sporadic layers, situated one above the other, is a usual phenomenon of the mid-latitudinal ionosphere, it was straightforward to investigate a three-dimensional model of two layers with finite horizontal dimensions too. The one layer was considered to be the current generator. The second layer was taken to be the load. It was assumed that the first layer, the "generator", is influenced by the action of the neutral wind which is caused by the acoustic waves. But on the second layer, the "load", situated below the first layer, the neutral wind does not act. In such a current system of two horizontal sporadic Es-layers of different plasma density and with currents along the magnetic field lines connecting the borders of the sporadic layers, according to the analysis, the generation of Farley-Buneman turbulence with a frequency of 10^3 s^{-1} is possible. Besides, if the sporadic layers are sufficiently thick and dense, the currents along the magnetic field lines in the external current system may excite the ion-sound instability, and the plasma of the ionosphere is intensively heated.

Thus, if before or during the earthquake in the near-Earth atmosphere near the epicentre appears a sufficiently strong low-frequency acoustic activity, so the mentioned mechanism of seismo-ionospheric coupling may occur. It has to be underlined, that the model supposes spatial localization - the horizontal scale of the local currents may be of the order of some kilometres. The related atmospheric heating may be also the reason of a local increase of the atmospheric optical emissions. The characteristic horizontal dimensions of the optical phenomena should be of the order of some tenths of kilometres.

3.4 Electromagnetic models

3.4.1 "Resonance" model

One of the first models of lithosphere-ionosphere coupling before earthquakes was the "resonator" model [Gokhberg et al. 1985]. There it was suggested, that before earthquakes, near the epicentres, there occur processes of short-time charge separation at the planetary surface with time scales of 10^{-3} s. These processes cause currents and charges in the ionosphere, and further oscillatory processes in the system lithosphere-ionosphere - in analogy to usual current systems with capacity, induction coil and resistivity.

Thereat, electromagnetic energy is transferred from the lithosphere into the ionosphere, and heating and its consequences occur in the E-layer. Taking the block structure of the Earth's core into account, and suggesting that the characteristic dimensions L of the earthquake preparation zone of not too strong earthquakes are of the order of H, where H is the effective distance between the surface of the Earth and the E-layer of the ionosphere, it is possible to roughly estimate the capacity of the lithosphere-ionosphere system in the earthquake preparation zone as $C = \varepsilon_o H$ and the induction as $L = \mu_o H$. Therefrom follows an estimate for the oscillation period $T = 2\pi(LC)^{1/2} = 2\pi H(\varepsilon_o \mu_o)^{1/2}$. Thus at $H = 100$ km, one finds a frequency of $f \approx 0.5$ kHz. But although for a series of earthquakes the electromagnetic effects were analysed in the VLF interval [Gokhberg et al. 1988], up to now, there exist no experimental confirmations of the resonance hypothesis. Thus it follows that resonance ionospheric effects, if they even cannot be neglected principally during earthquake preparation [Tate and Daly 1989, Tate 1990], do not play an important role in the lithosphere-ionosphere coupling.

3.4.2 Model considering the transformation of broadband electromagnetic emissions to Alfvén waves

In the work by Molchanov [1991] a model was proposed according to which during the shift and distruction of blocks of the Earth's core along active fractures, near the centre of a preparing earthquake, broad-band electromagnetic emissions are generated. There it was assumed that the region of the generation of the emissions has a dimension of 100-150 km. Electromagnetic emissions generated by elastic oscillations in the Earth's core are considered in [Guglielmi and Pokhotelov 1996, Sgrinya et al., 2004]. There exist two mechnisms of the excitation of the emissions, the inductive one and the electrokinetic one. The first mechanism bases on the appearance of Fuko currents during the motion of the Earth's core in the geomagnetic field. The second mechanism is connected with the motion of the fluids in the pores and fractures of the rocky material. The emissions propagate through the Earth's crust and surface, the atmosphere and ionosphere. Their spectrum changes by the interaction of the charged particles of the near-Earth plasma, and they cause Alfvén waves with frequencies of 0.3-10 Hz in the plasma of the upper atmosphere and magnetosphere. The hypothesis was made to explain anomalous very low-frequency (VLF) emissions in the ionosphere above seismo-active regions, which were obtained by satellites.

3.4.3 Coupling by series of electromagnetic field pulses

Within the model by Kolokolov et al. [1992], it was assumed that the connection between ionospheric and lithospheric disturbances is realized by a series of pulses of the electromagnetic field. It has to be mentioned first, that in a series of works it was found that a few days before an earthquake, near the epicentre pulses of the atmospheric electric field of $\delta E \leq 10^3$ V/m were repeatedly obtained. And the amplitudes of the variations of the magnetic field, registered at the same time, amounted to $\delta B = 1 - 10$ nT [Gogatishvili 1984, Kolokolov et al. 1992]. Let us make now an rough estimate which shows that the excitation of disturbances with characteristic time scales of $\tau_1 = 1 - 0.1$ s is possible.

It is assumed that at the Earth's surface, due to any reasons, during the preparation process of a strong earthquake with $M = 5 - 6$, the charges are divided into groups of positive and negative ones with a characteristic time scale τ_1 and with a characteristic length scale equal to the dimension of the earthquake preparation region $L \approx (10 - 100)$ km. The total electrical current equals $I = Q/\tau$, and the estimate of the intensity of the electrical field near the Earth's surface, in the case of an homogeneous distribution of the charges on an area of the order of L^2, gives $\delta E \approx Q/2\varepsilon_o L^2$. If, besides, the electric current is homogeneously distributed in a plane sheath of width L, one obtains for the variations of the magnetic field $\delta B = \mu_o Q/2L\tau^1$. From that it follows for the characteristic time scale of the process $\tau_1 \approx \mu_o \varepsilon_o L \delta E/\delta B$. Substituting the above mentioned experimental values of δE, δB and L, one has $\tau_1 \approx 1$ s, and a maximum charge of $Q = 200$ C. Thus, the here made estimate shows that electromagnetic processes with characteristic time scales of 0.1-10 s are possible in the earthquake preparation zone on condition that an rather quick separation of charges occurs. Some results of observations of activity pulses of electromagnetic processes before earthquakes with the discussed time scales are published in [Fraser-Smith et al. 1990, Tate 1990]. In the E-layer of the ionosphere, at altitudes of the same scales of $L \approx$100 km above the region of the charge separation, there should occur induced charges of the same order of magnitude $Q^* \leq Q$", distributed in a region of the same length scale. The corresponding field-aligned potential electric fields $\delta E_\parallel^p$ may be found using the Ohm's law $m\nu_{en} V_\parallel \approx e\delta E_\parallel$ and the relation $Q^*/\tau_1 \approx S_{eff} n_e V_\parallel$, with $S_{eff} \approx L^2$ cosα (α is the tilting angle of the field lines of the magnetic field to the vertical). The estimate of the maximum field-aligned electric field in the ionosphere at $L = 10^5$ m, $n = 10^3$ cm^{-3}, $\nu_{eff} = 4 \cdot 10^4$ s^{-1} and cos $\alpha = 0.3$ gives $\delta E_\parallel \leq Q^* m\nu_{en}/\tau_1 L^2 ne^2 \approx 3{\cdot}10^{-4}$ V/m, which is in agreement with the observations.

The effects of anomalous blurring of the sporadic E-layer in the ionosphere before earthquakes, which were investigated in [Alimov et al. 1989, Kolokolov et al. 1992, Liperovsky et al. 1993], may be interpreted, if one suggests that heating occurs and that the temperature change is of the order of the electron temperature, $\Delta T_e \approx T_e$. The relation for the Joule heating of the ionospheric plasma under the condition of a field-aligned current reads $\partial T_e/\partial t \approx m V_\parallel^2 \nu_{en} - \delta(T_e - T_n)\nu_{en}$. Here δ describes the part of the energy which is transferred from the electrons to the neutral particles due to collisions. In the case of elastic collisions one has $\delta = 1.6{\cdot}10{-}3$. At $\tau_1 \approx 1$ s, neglecting the non-stationary term, it follows $T_e - T_{en} = \Delta T \approx m V_\parallel^2/\delta$. Thus, at a velocity $V_\parallel \approx (T_e \delta/m)^{1/2} \approx 3 \cdot 10^3$ m/s and a temperature $T_e = 0.03$ eV, according to Ohm's law, $m\nu_{en} V_\parallel = e\delta E_\parallel$, the field-aligned electric field amounts to $\delta E_\parallel \approx 7 \cdot 10^{-4}$ V/m.

The generation of such field-aligned electric fields is possible, if at the Earth's surface local charges occur with $Q >$ 200 C or if there are quicker processes of charge separation (e.g. with time scales $\tau = 0.2{-}03$ s) and the charge intensity is less. Using for the blurring time of the sporadic E-layer the relation

$$\tau_D \approx 1.6/D \approx 1.6a^2 M\nu_{in}/k(T_e + T_i),$$

with a thickness of the sporadic E-layer of $a = 100{-}1000$ m, the ambipolar diffusion coefficient D, and T_e and T_i - the temperatures in Joule, one finds for a thickness of the sporadic layer of $a = 150$ m and a coefficient of ambipolar diffusion $D = 60$ m/s a life time of the sporadic layer of $\tau_D \approx 15$ min, which is in agreement with the strong decrease of the density of the sporadic layer before earthquakes.

Thus, electric fields of seismic origin of the order of 10^3 V/m near the surface of the Earth with horizontal dimensions of the order of 100 km may strengthen processes of ambipolar diffusion in the ionosphere and decrease the characteristic time scale of the blurring of sufficiently narrow sporadic E-layers (with a thickness below 100 m). More intense heating processes and the blurring of thicker layers must be caused by much stronger electric fields. Thus the hypothetic mechanism of charge separation at the Earth's surface is not sufficient to explain all observations.

4 Conclusions

Thus in the review, a critical analysis of present experimental data and theoretical models concerning the lithosphere-atmosphere-ionosphere coupling during earthquake preparation times is presented. Up to now, no generally accepted theoretical hypothesis exists, which would allow to interprete the observations of ionospheric disturbances occuring some days before even strong earthquakes. On the other hand, no mistakes of the different, recently existing hypotheses could be found - not of the hypothesis of the generation of acoustic-gravity waves, the hypothesis of the modification of the electrical conductivity in the near-Earth atmosphere because of radon injection, the hypothesis of the generation of an Es-generator and of mini-current systems in the night-time E-layer because of acoustic pulses, the hypothesis of the excitation of resonance oscillations in the system Earth-ionosphere, and not of the electromagnetic hypotheses according to which lithospheric disturbances of the electro-magnetic field are directly transferred through the atmosphere into the ionosphere. Thus, one has to conclude that, in reality, in nature obviously different physical mechanisms act, and only some of them are mentioned in the present review.

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