Modification Of Sporadic E-Layers Caused By Seismic Activity

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CONTENTS

1 Introduction

Every year in the world more than 100 earthquakes of large magnitude appear causing many victims and destructions. The search for possibilities of earthquake prediction using traditional seismological methods has already been carried out for many years (e.g., Gokhberg M.B. et al., 1995 and references therein). One believes, that the problem of long-term prediction is solved in principle. But the problem of short-term earthquake prediction, some tens of hours before an earthquake, is yet one of the most important unsolved problems of modern geophysics. Recently, one tries to deal with the problem of short-term prediction introducing non-traditional methods, e.g., methods based on electromagnetic and ionospheric earthquake precursors. In due time, the problem related to the study of interrelations between specific processes in the ionosphere and earthquake preparation zones was raised. Nowadays, it is experimentally established that at different altitudes and, accordingly, in different ionospheric regions, various specific phenomena occur, which seem to be caused by lithospheric processes and appear a day or some hours prior to a relatively strong earthquake.

The ionospheric processes contain regular and irregular variations. Usually, ionospheric disturbances are considered mainly in connection with the solar influence alone. But recently (in the seventies) it was recognized that the ionosphere is also sensitive to processes in troposphere, hydrosphere and lithosphere. Volcanic activity, tsunamis, earthquakes, cyclones, thunderstorms, satellite and rocket launches, the effect of overcoming the supersonic barrier, strong ground and underground explosions, radio, acoustic and thermal signals - all these phenomena influence the ionosphere.

In the given paper, a review of ionospheric phenomena caused by earthquakes at E-region altitudes, i.e. between 90 km and 130 km above the Earth's surface, are presented.

Most of the data of E-region parameters are obtained by means of ground based vertical sounding (VS) experiments. Under day-time conditions at the altitudes under consideration, there exist both regular E-layers and irregular formations, that means sporadic E-layers (E_s). During the night-time, the plasma density of the regular E-layer is normally rather low. No trace of the ionisation can be found in the ionograms, and only sporadic E-layers can be studied.

In what follows the main attention is paid to the investigation of this phenomenon in mid-latitude night-time sporadic E-layers. The night-time is chosen in order to avoid the direct solar influence.

At present time some physical models describing the connection between ionospheric anomalies and processes in the Earth's crust are under discussion. Conditionally, the lithosphere-ionosphere coupling models during the earthquake preparation can be grouped into "electromagnetic" and "acoustic" models.

The first model suggests that during earthquake preparation, earth currents, electrically charged spots, and electromagnetic hiss emissions appear. Under the action of the electromagnetic field of lithospheric origin, the ionospheric parameters are modified. On the contrary, the second model assumes that generation of acoustic disturbances in the near-earth neutral atmosphere is caused by lithospheric processes. Acoustic and acoustic-gravity waves then may propagate up to ionospheric altitudes and, thanks to collisional processes, excite disturbances in the ionospheric plasma.

The determination of the characteristic modifications in the ionospheric parameters before earthquakes, and of the relevant spatial and temporal scales of the modifications gives the possibility to proof experimentally the reliability of the models and to discover the mechanism of seismo-ionospheric coupling, which is necessary for further development of reliable methods of earthquake prediction.

2 Formation and destruction of sporadic E-layers

Now some important information about ionospheric sporadic E-layers (see Whitehead J.D., 1989) should be reminded taking into consideration in particular the ionosphere of the middle latitudes.

The E-region of the ionosphere stretches from the height of 90 km to 160 km. At day-time, its density amounts to $N < 10^{11}$ m^{-3}. During night-time, it is about two orders smaller than during day-time. The dominant ions of the E-region are attributed to O_2^+ and NO^+. The other species, among them the metallic ions, form only a small fraction (few percent) of the total ion content.

Sporadic E-layers have been observed at mid-latitudes between 90 km and 140 km. They represent specific plasma clouds of metallic ions having small vertical and large horizontal dimensions. For the formation of sporadic layers it is necessary that the recombination coefficient has to be below 10^{-2} m^3/s. The typical ionospheric ions, i.e. O^+ and NO^+, do not satisfy this condition. Owing to this fact, they are formed by essentially longer living metallic ions Mg^+, AL^+, Fe^+, and Mn^+, which the ionosphere contains in sufficient quantities.

The formation of sporadic E-layers is often attributed to the occurrence of shear winds. According to this model, the sporadic layers are formed at the altitude where the local zonal wind changes its direction from west to east, i.e. in the region with wind shear. If, at some altitude in the E-region, the horizontal wind changes its direction to the opposite one, then charged particles are piled up into a region, where the divergence of the wind velocity $\mathbf{V}$ vanishes, $\vec{\nabla} \cdot \vec{V} \to 0$, and the vertical gradient of the velocity is about 0.05 – 0.06 s^{-1} or more. Thus, a sporadic layer is formed. The spreading of sporadic layers is mainly controlled by ambipolar and turbulent diffusion.

One of the widely used critical frequencies is the so-called screening frequency $f_b E_s$, which is chosen to describe the maximum plasma density in a layer; $f_b E_s \sim (N_m)^{1/2}$, where N_m designates the maximum ion number density. Its value may reach $10^{11} - 10^{12}$ m^{-3}. The thickness of sporadic layers is between some hundreds of meters and some kilometers. The horizontal dimensions of the sporadic E-layers have been found to be about 100 km, and up to 200 km. Sometimes the layers exhibit a fine-structure in horizontal (ionisation spots) and vertical (stratification, spread-E) directions. Vertical motions of sporadic layers down to lower altitudes with velocities of 0.1 - 3 m/s and horizontal motions with velocities of 30 - 150 m/s were observed.

If the sporadic E-layer consists of long-living metallic ions, the destruction time of the sporadic layer lasts for some tens of hours if only ambipolar diffusion is in operation. Under such conditions, the horizontal displacement of the layer usually amounts to some hundreds of kilometers. If turbulent pulsation appear in the neutral component, the effective diffusion undergoes a significant increase.

According to modern classification, in the night time at mid-latitudes usually layers of two types are found: f (flat) and l (low). The l-type layers are rare enough. The f-type layers exhibit a "flat" trace, the reflection height is not essentially higher at larger frequencies. Here, it is worth mentioning that one tried to compare these different types of sporadic layers with various phenomena occurring in connection with seismic activity, but no direct relations were found, and this negative result has never been published.

Another characteristic parameter of the layer refers to the f_oE_s-frequency, at which the layer is evanescent for the ordinary mode. This frequency rather strongly depends on the characteristics of the vertical sounding station, the absorption level of the radiowaves, and the electron concentration profile in a sporadic layer (Takefu M., 1989), and, as it was supposed last years, f_oE_s is controlled by plasma turbulence in the sporadic E-layer (Eroukhimov L.M. and Savina O.N., 1980).

As a sporadic E-layer is not a regular formation, it is customary to introduce the probability of appearance (PA) for every vertical sounding station. The PA is usually defined as the ratio of the number of appearances to the total number of measurements multiplied by 100 %. Certainly, the PA depends on the sensitivity of the radio apparatus and the minimum sounding frequency. Moreover, the PA is also a complicated function of the geographic coordinates, and it has seasonal and daily variations. The PA seasonal variations exhibit maximum values in summer time. The latter fact is especially important in relation to the study of seismo-ionospheric phenomena, as one of the investigated parameters, the variability of the sporadic layer with time, loses its physical sense at low values of PA.

Another important characteristics of sporadic E-layers corresponds to the relevant altitude $h'E_s$. Various investigations of the dependence of the relevant altitude $h'E_s$ on the day-time and season have been performed. There were found $h'E_s$-variations with a timescale of some minutes (Whitehead J.D., 1989).

A large number of rocket experiments demonstrates a fine-structure in sporadic E-layers. According to (Takefu M., 1989), such a fine-structure, even if the disturbance is rather small, can cause essential modifications of the trace in the ionogram.

3 Temporal variations of parameters of sporadic layers during earthquake preparation

3.1 Temporal variations of f_bE_s with time-scales of few hours

A question devoted to time-scales of seismo-ionospheric effects was discussed in a number of papers. Time-scales from few hours to few minutes were analysed.

Using the data of Dushanbe and Petropavlovsk-Kamtshatkiy stations, Kolokolov et al. (1992) provided the analysis of the night-duration of sporadic layers for earthquakes of classes $K > 12$ at distances $R < 300$ km from the VS-stations. The analysis was limited by considering time intervals between 22.00 LT and 06.00 LT. If an earthquake happened at day-time, the night before the earthquake was taken as night (-1). If it was a night-time earthquake, the (-1) night was assumed to be the night during which the most time passed before the shock. The conclusion was that the probability of the sporadic layer appearance decreases hours before an earthquake in comparison with the layer appearance two days before the earthquake.

It is only reasonable to investigate the probability of appearance for winter time when this probability is small. Further, the probability parameter should be used for stations with large minimum sounding frequency f_{min}, e.g. when $f_{min} \approx 1.0 - 1.2$ MHz.

In summer, the E_s-trace is always available on the ionogram, especially if $f_{min} \approx 0.05$ MHz. Because of this reason the effect of variation of the mean frequency f_bE_s in summer was examined in the papers (Alimov O.A. et al., 1989, Liperovskaya E.V. et al., 1994).

Table 1: Distribution of the parameter Δ for seismoactive nights with earthquakes of different magnitude, and for background nights.

	$\Delta < 0.9$	$0.9 < \Delta < 1.1$	$\Delta > 1.1$
s/a nights, (-1), $4.5 < M < 5$	19	13	25
s/a nights, (-1), $M \geq 5$	33	13	12
background nights	279	181	277

If the E_s-layer trace was absent on the ionogram, the value of f_bE_s was taken equal to the minimum operating frequency of the VS-station. To study this behaviour, a new parameter Δ equal to the ratio of the mean night-time frequency f_bE_s to the mean night-time frequency of the preceding night was introduced (Liperovskaya E.V. et al., 1992, 1994).

The table 1 demonstrates the distribution of the parameter Δ for seismoactive nights and background nights. More than 700 nights of the years 1985 to 1989 were examined for the stations Dushanbe, Alma-Aty and Ashkhabad. Two groups of nights were examined: (-1) nights for earthquakes with $M \geq 5$, (-1) nights for earthquakes with $4.5 \leq M < 5$. The distances between the epicentre and the VS-station were not larger than 500 km. All other nights were taken as background nights. As a variability signature the parameter $\tilde{\chi}^2$ was used, and the authors came to the conclusion, that for earthquakes with magnitude $M > 5.0$ appearing at a distance $R < 500$ km from the VS-station, the mean characteristic frequency f_bE_s during the (-1) night decreases in comparison with the night (-2), and this process is not random with the probability more than 99%. No decrease of the parameter Δ was found for earthquakes with $M < 5$.

3.2 Study of f_bE_s variations with characteristic time-scales of 0.5 - 3 hours

A search for variations of the parameters of E-layers with characteristic time-scales of 0.5 - 3 hours was carried out in the paper (Popov K.V. et al., 1997). The authors made the conclusion that the usual spectral analysis is unsuitable for detection of the fine seismo-ionospheric effects in the time variations of the frequencies f_bE_s. First, the time behaviour of this frequency clearly correlates with the season. If the harmonic amplitudes are averaged over the month or season, the number of nights before the earthquakes is too small to get statistically well-founded results, in comparison with the average harmonic amplitudes of the quiet background nights of the same periods. Secondly, the standard vertical sounding is carried out every 15 minutes. Thus, there are only 33 values for every conventional night with intervals of 8 hours, and every night corresponds with 16 harmonics. In other words, the application of the usual spectral analysis proposes the existence of a periodic process. In the contrary case, a spectrum of only about 16 harmonics will correspond to every type of disturbance. Thus the authors of the paper (Popov K.V. et al., 1997) have analysed bay-formed variations, that means step-like increases or decreases of the parameter $f_b E_s$ to relatively constant values, and further step-like decreases or increases to the initial undisturbed values.

The physical mechanisms connected with the formation of bay-type variations are different in dependence on the different characteristic time-scales and seasons. A bay-formed density-increase can be caused by the motion of the ionospheric sporadic layer above the station, by the formation of the sporadic layer as a result of wind-shear, by the formation of a sufficient dense layer as a result of superposition of two layers of lower density, so that one layer alights on the other layer. A bay-type density decrease may be connected with a spotted structure of horizontally moving clouds of one sporadic layer.

The first two nights before an earthquake (named (-2) and (-1) nights) were called seismoactive in the analysis. The remaining nights (besides the night (+1)) after the earthquake were taken as background nights. Only earthquakes with magnitude $M \geq 5$ were taken into account, where the distance of the epicentre to the VS-station was not larger than 1000 km. In the paper (Popov K.V. et al., 1997), basing on long-lasting observations, the authors came to the conclusion that the average number of bays per night with shortest time scale $\tau_1 \leq 0.5$ hours has a tendency to decrease during seismoactive nights in comparison with the background nights. The number of bays with time-scale $\tau_3 = 2 - 3$ hours has a tendency to increase during seismoactive nights in comparison with the background nights. For bays with mean time-scale $\tau_2 = 0.75 - 2$ hours, the average number is almost equal for seismoactive and background nights.

3.3 Variations of the parameters of sporadic E-layers with characteristic time-scales of 15 - 45 minutes

In a number of papers devoted to the revealing of seismo-ionospheric effects with time-scales mentioned above, a new parameter to evaluate $f_b E_s$ disturbances was introduced, the so-called "cut-off" number of $f_b E_s$. "Cut-off" corresponds to abrupt $f_b E_s$-decreasing, not less than 0.8 MHz during 15 minutes. It was revealed, that the "cut-off" number in (-1) and (-2) nights before an earthquake increases in comparison with background nights (Alimov O.A. et al., 1989).

In the papers (Liperovsky V.A. et al., 1993, Liperovskaya E.V. et al., 1995) the behaviour of sporadic E-layers during earthquake preparation was studied using the extensive data base.

For convenience, in these works the dimensionless parameter $\Delta f/f = 2[f(t+15) - f(t-15)]/[f(t+15)+f(t-15)]$ was used. As night the hours between 22.00 LT and 06.00 LT were considered. The night (-1) was defined as it was done by (Kolokolov et al., 1992). In the case of the lack of a trace in the ionogram, the f_bE_s-value was assumed to equal the sensitivity threshold of the VS-station. The station of Dushanbe has a threshold of 0.5 MHz.

It is clear, that for every shortened night 32 values of $\Delta f/f$ exist. In Figure 1, the histograms of $\Delta f/f$ of the night of the 23 September 1987 and of the mean value of $\Delta f/f$ for September 1987 are given. The histograms are antisymmetric: the number of negative $\Delta f/f$-values is larger than the number of positive values, as until the morning hours the density of the sporadic E-layers decreases because of recombination effects. Within the interval (-0.1,0.1) the histograms are symmetric, as there exist small subintervals with f_bE_s = const, and thus the data are averaged within the intervals (-0.1,0.0) and (0.0,0.1). A very insignificant number of cases with $|\Delta f/f| > 0.8$ is included in the intervals (-0.8,-0.7) and (0.7,0.8).

The distribution $\Delta f/f$ presented in the histogram is characterized by the two parameters $\langle \Delta f/f \rangle$ and σ. The mean value $\langle \Delta f/f \rangle$ is about zero, its variations were not investigated. The dispersion σ of the histogram characterizes the variability of a sporadic layer during one night. It is necessary to underline that the histograms for the mean monthly values change from month to month. During the autumn-winter months, when sporadic E-layers often do not exist, the number of cases with zero value of $\Delta f/f$ strongly increases, thus the histogram becomes more variable than during the summer time. For instance, the mean value $\tilde{\sigma} = 0.33$ in May 1985, and $\tilde{\sigma} = 0.26$ in November 1985. That is why the variability of σ with respect to $\tilde{\sigma}$ has to be considered for every month separately. In March and April often cases are found, where no sporadic layer forms during the whole night. Thus the frequency f_bE_s is constant and equals the threshold of sensitivity of the VS-station, and the value of σ for such nights is zero. These nights were excluded from the study.

In the paper (Liperovskaya et al., 1991), an increase of dispersion σ was observed, where σ was found for the sum of all seismoactive nights (-1) and (-2) of the given month. Earthquakes with $M > 4.5$ and $R < 300$ km were considered, occurring during 10 of the 11 studied months. In the papers (Liperovsky V.A. et al., 1993, Liperovskaya E.V. et al., 1995) the parameter σ for the histograms $\Delta f/f$ was compared for seismoactive and background nights for every month. Three periods of time were considered: 1985, 1986, 1987 (233 nights), 1988 (197 nights), 1989 (183 nights). As a variability signature the dimensionless parameter χ_o^2 was used. It was revealed that the variability increases for the night (-1) with a probability of appearance of more than 95 %, which shows that the effect is not random.

3.4 Sporadic E-layer variations with characteristic time-scales of 2 - 15 minutes

Some ionospheric effects with time-scales of a few minutes were found in the Doppler-sounding experiments of the F-region. Frequency variations in Doppler experiments correspond to the variations of the velocity of charged particle clouds. In the papers (Liperovsky V.A., Senchenkov S.A. et al., 1997, Toroshelidze T.I., Fishkova L.M., 1988) processes with time-scales of some minutes were discussed. In the second of these papers (Toroshelidze T.I., Fishkova L.M., 1988), anomalous variations with time-scales of 3 - 10 minutes of the night airglow intensity at wave length 5577 Å were found. In the paper (Liperovsky V.A., Senchenkov S.A. et al., 1997), the authors analyzed 1-minute ionospheric sounding data of the station Dushanbe (38.5 N, 68.8 E). 1-minute ionospheric observations were provided during only one month, and no strong and close to the station earthquakes occurred, so no earthquake precursor effects were found. As it was already mentioned, the f_bE_s frequency corresponds to the maximum electron density in the layer, f_oE_s corresponds to the small-scale spatial irregularities in the layer, but no effective parameters, which correspond to the vertical motions of the layer may be found.

In connection with the seismic activity an intensification of the disturbances of the sporadic layers with time scales of $\tau_1 \approx 2 - 5$ min and $\tau_2 \approx 5 - 10$ min was obtained after the earthquakes of 25.-26.09.88. These results are in qualitative correspondence with the results of the work (Toroshelidze T.I. and Fishkova L.M., 1988), where wave-like fluctuations of the parameters of the ionospheric F2 layer with periods between 2-3, 5 and 10 minutes were found using the methods of spectral analysis.

Further, the high variability of the parameter $\Delta_f = f_oE_s - f_bE_s$ should be mentioned, which, as known, characterizes the turbulization of a sporadic layer. The variations of the interval of semi-transparency are also demonstrated in Figure 2, showing the temporal behaviour of Δ_f during the night of 26-27.09.88.

The main result of the paper (Liperovsky V.A., Senchenkov S.A. et al., 1997) is that the ionospheric sporadic layers possess a rather strong variability with time scales of some minutes. The spectral densities of the characteristic frequencies can be used as important characteristics of disturbances of lithospheric origin. Besides, during seismic activity the variability of sporadic E-layers with time-scales of some minutes may increase, which can be connected with turbulization processes in the ionospheric E-layer under the action of acoustic and acoustic-gravity disturbances.

4 On the spatial scales of sporadic E-layer disturbances related to seismic activity

In all papers which were discussed in the previous paragraph, f_bE_s variations were studied by using single-position measurements. Meteorological, anthropogenic and other geophysical effects interfere with seismo-ionospheric effects.

One of the most critical points in the study of seismo-ionospheric phenomena is how to exclude the quasi-global background variations, i.e., the search for means how to single out most effectively the signal against the background. Liperovskaya et al. (1994) studied the spatial scales of seismo-ionospheric phenomena using data of earthquakes with $M > 4.5$ of five VS-stations. The ionospheric stations were separated one from another at a distance of 300-1700 km. Under such conditions it seems to be possible to distinguish between the effects before earthquakes and phenomena caused by meteorological, solar and other global effects influencing sporadic E-layers.

It was found (Liperovskaya et al., 1992) that a few hours before an earthquake the E_s-spread phenomenon appears. But the sporadic E-layers are rather variable themselves. Thus, it is quite difficult to determine whether the decrease of the mean f_bE_s is caused by seismic phenomena and not by solar or pure meteorological reasons.

One of the most simple possibilities is to study the linear correlation between any mean sporadic layer characteristics for two VS-stations, assuming that the effects, remaining after the elimination of the quasi-global anomalies, are connected with the earthquake preparation in the seismic zone.

It was assumed that for ionospheric stations situated at distances of about 100 km from the epicentre, all non-seismic factors will be almost the same. During seismically quiet time, the mean night-time f_bE_s-values of near stations should be well correlated. To reveal the effects of seismic origin, the correlation between the mean night-time f_bE_s-values obtained by several VS-stations of middle Asia during earthquake preparation and background periods was investigated.

Table 2: Correlation coefficients of the mean night-time parameters f_bE_s, $R_{epic} \leq 1000$ km, S/A - seismoactive nights, B/G - background nights.

Coupled stations	R	S/A N	S/A $k/\delta k$	B/G N	B/G $k/\delta k$
Dushanbe-Tashkent	310	29	0.50 0.15	37	0.80 0.06
Tashkent Alma-Aty	760	37	0.30 0.20	47	0.79 0.05
Dushanbe-Alma-Aty	870	32	0.60 0.10	38	0.84 0.05
Karaganda-Tashkent	1020	36	0.30 0.10	48	0.67 0.07
Karaganda-Dushanbe	1300	37	0.20 0.20	53	0.63 0.06

The data used were found by the VS-stations Dushanbe (38.5 N., 68.8 E), Alma-Aty (41.3 N., 76.9 E), Tashkent (41.3 N., 69.6 E), and Karaganda (49.8 N., 73.1 E). The time interval between two measurements was one hour. The behaviour of the sporadic E-layers was investigated for night-time conditions only, to avoid the direct influence of the solar radiation. The time from 21:00 LT to 05:00 LT was considered to be the night. The results are shown in Table 2.

The column "stations" of the Table 2 give the pairs of stations for which the linear correlation coefficients k are calculated. Here r was defined as the distance between the stations, and N is the number of investigated nights. In the lower sublines of the column "k", the statistical error δk of the correlation coefficients is given. This error can be estimated by the square root of the dispersion δk of the correlation coefficient. Earthquakes with $M > 4.5$ are investigated (e.g., ISC Bulletin 1985, 1987). The periods of earthquake preparation are again the (-2)- and (-1)-nights. All other nights are considered to be background.

In the column "total" the calculated correlation coefficients are represented assuming that earthquake preparation processes do not influence the sporadic E-layers. In the next column, the correlation coefficients for the periods of earthquake preparation and background nights are presented separately, assuming that the preparation processes influence the ionosphere if at least one of the stations of the chosen pair of stations has a distance to the epicentre $R < 1000$ km.

¿From the analysis of the mean characteristics of the ionospheric sporadic E-layers the following conclusion can be made: The preparation processes influence the mean characteristics of ionospheric sporadic E-layers, when the distance of the VS-station from the epicentre is less than 1000 km.

5 Complex experimental researches of the ionosphere, electromagnetic noise and geomagnetic field

5.1 Ionospheric and electromagnetic phenomena of the Kayraccum earthquake in 1985

Evidently, investigations of one of the ionospheric parameters in one chosen point of observation in the period of earthquake preparation for a number of events provides a way to justify seismo-ionospheric links statistically and to evaluate it. But up to now the problem of the physical mechanisms of seismo-ionospheric coupling exists. To solve this problem, it is principally necessary to investigate complexes of simultaneous data of different geophysical parameters for different frequency ranges at different altitudes in a number of points of the seismo-active region. In the paper (Liperovsky V.A. et al., 1998) seismo-ionospheric effects caused by the Kayraccum earthquake in Tadjikistan were considered. The earthquake had happened on October 13, 1985, 21:59 LT, the coordinates of the epicentre were $\varphi = 40.3^o$ N, $\lambda = 69.8^o$ E, the depth of the epicentre amounted to $h = 3$ km, the magnitude was about 6.0. Data material of six days is analysed starting with the measurements three days before the earthquake and finishing with the data of the third day after the event. It should be mentioned that, in comparison with the other months, in October 1985 also a larger number of earthquakes of smaller magnitudes happened in the surroundings of Kayraccum. One earthquake of small magnitude was registered three days before the Kayraccum earthquake. This gave the reason to limit the investigated period to three days before the event. The investigation mainly bases on the ionograms of the vertical sounding station Dushanbe situated about 220 km from the epicentre of the Kayraccum earthquake.

In the Figures a-c, results of the investigation of the sporadic layers above the territory of the earthquake are presented. The mean values of the characteristic frequency f_bE_s per night as function of the time are shown in Figure 3a. The frequency f_bE_s is the minimum frequency at which the sporadic layers become semi-transparent. It should be mentioned that f_bE_s is proportional to the square root of the maximum electron density in the sporadic E-layer. In the case of lack of traces of sporadic layers in the ionograms, the value of the f_bE_s frequency was taken to be 0.4 MHz. It can be seen, that in the nights (-2) and (-1) before the earthquake the f_bE_s frequency is decreased. This is in accordance with the results of statistical investigations, showing that in the first night (-1) before an earthquake with magnitude $M \geq 5.0$ the $f_b E_s$ value usually decreases. It was found that in the case of very strong earthquakes with $M \geq 6.0$ the decrease occurs during two days.

In Figure 3b, the total time of observation of the sporadic layer per night is given as function of the nights. This total occurrence time decreases before the earthquake, which is in agreement with results of (Kolokolov E.A. et al., 1991).

The number n of strong changes of the $f_b E_s$ frequency per night as function of the time is presented in Figure 3c. Changes of $f_b E_s$ of more than 0.6 MHz during 15 minutes were considered as strong ones. In the paper (Liperovsky V.A. et al., 1993), it was obtained that the variability of the characteristic frequency $f_b E_s$ increases during the nights (-2) and (-1) before earthquakes with magnitudes $M \geq 4.5$ and distances between the epicentre and the sounding station of $R \leq 500$ km. From Figure 3c, it follows, that before the Kayraccum earthquake the variability grew. After the earthquake the variability decreased. The value of n in the nights (-3) and (-2) is larger than the mean value of the whole month.

In the paper (Popov K.V. et al., 1997) it was obtained, that about two days before an earthquake with magnitude $M \geq 5$ the number of bay-formed disturbances in the temporal behaviour of the frequencies $f_b E_s$ and f with characteristic time-scales of τ = 2-3 h increases. $f(h' = 300)$ is the minimum frequency of the reflection of the ordinary wave in the F2-region at an altitude $h' = 300$ km. It may be possible that before the considered Kayraccum earthquake with $M = 6.0$, short-time precursors occurred not two but already three days before the event. In the three nights before the event, in the temporal behaviour of the frequency $f_b E_s$ four “positive” bay-formed disturbances with characteristic time-scales of τ = 2-3 h were found. During the three nights after the earthquake, bay-formed disturbances with such time-scales were not observed. The numbers of bay-formed disturbances with time-scales of τ=1-2 h before and after the earthquake were equal.

Besides, in Figure 3d the number of bay-formed disturbances m of the frequency $f_o(h' = 300)$ is shown. f_o is the frequency of radiowaves of the vertical sounding station which are reflected at altitudes of $h' = 300$ km. This frequency is especially used for studies of density modifications of the ionosphere in the lower part of the F2-region. Using this parameter, the increase of the number of bay-formed disturbances before earthquakes is observed.

The analysis of the temporal behaviour of the mentioned ionospheric parameters confirms that ionospheric phenomena caused by earthquake preparation processes are activated about two days before an event. Further, these phenomena seem to be the reason for the heating of the ionosphere and the decrease of its mean density as well as its growing variability. Besides, in accordance with statistical regularities, the number of the large-scale disturbances lasting 1-2 hours increases in the E-region and the lower F2-region.

Some electromagnetic effects preceding the Kayraccum earthquake were investigated in (Hussametdinov S.S. et al., 1989). Studying natural impulsive electromagnetic radiation (EMR) with frequencies of about 2.5 MHz two-three days before the earthquake, an increase of EMR was registered.

5.2 Comparison of anomalies with characteristic time-scales of 2-3 hours for ionospheric E- and F-layers and temporal behaviour of electromagnetic noise emission intensity

As shown in paragraph 3.2, the number of bay-formed variations with characteristic time-scales of 2-3 hours increases with the time before an earthquake.

Here it should be mentioned, that the search for ionospheric effects of earthquake preparation with scales in the interval from 0.5 to 5 hours was also carried out for a few parameters of the F-region and for the envelop of the intensity of the pulsed electromagnetic emissions of the earth.

In studies of effects of the F-region, the analysis of electron density variations at the conditional altitude $h = 300$ km was carried out (Liperovsky V.A. et al., 1990). This analysis based on calculations of the number and duration of bay-formed declines from the night time median (for ten days) of the frequency of the radiowaves, reflected at the conditional altitude. As a result of the analysis was shown, that the number of variations with time-scales $\tau \geq 2$ min increases about two times in comparison with the background values within 1-3 days before an earthquake. In the work was also mentioned, that the mean number of variations averaged over all values of $\tau \geq 0.5$ h was the same for both quiet and seismo-active nights.

During investigations of the temporal behaviour of the characteristic frequency f_oF2 before some earthquakes, it was also found that the amplitudes of the harmonics with scales of 2 - 3 hours increase (Gayvoronskaya T.V., 1991).

Further, already in the work (Bella F. et al., 1992), observations of the natural electromagnetic emissions (NEE) and of data of VS-stations in seismoactive regions during seismoactive times were presented. The NEE measurements were done during nearly five months in Italy in 1987. To avoid the influence of technogenic and atmospheric disturbances, the NEE registration system was put into a natural cavern under the Earth's surface. The NEE-signals were integrated by an RC-circuit with time constant equal to 10 min. Three frequency intervals were analysed: 0.3-3 kHz, 3-39 kHz, 30-300 kHz. The observations were performed during March-April and July-October in 1987. Before 17 earthquakes (with $0.3 \leq M \leq 4.8$), for which the station was situated within the effective radius of the earth-surface deforming action of the earthquake precursors, the spectrum of the bay-formed variations during the seismoactive (two days before the earthquake) and quiet periods was observed. Two days before an earthquake, the number of bay-formed disturbances of the envelope of the intensity of the electrical component of the emissions with time scales $\tau \approx 2$ - 3 h was about two times larger than during quiet times.

Thus it is probable that the intensity increase of the 2-3 h-variations of parameters at different altitudes and of the NEE near the Earth's surface 2-3 days before an earthquake of sufficient large magnitude have the same cause.

5.3 Night airglow emissions in the E-region before earthquakes and sporadic E-layer variations

Long-term observations of night airglow emissions in seismoactive regions of the former Soviet Union have been provided at Abastumani (Georgia) and Vannovskaya (Turkmenia) observatories.

It is well known that the most intensive emission in night airglow correspond to atomic oxygen lines. The emitting layer of atomic oxygen 5577 Å (green line) is situated at altitudes between 85 km and 110 km during the night-time in the mid-latitude ionosphere, i.e., in the E-region (Fishkova L.M., 1983). Thus, a certain correlation may exist between the photometric observations and VS-experiments during earthquake preparation processes.

On the one hand, the intensity of the oxygen green line strongly depends on the temperature and the neutral components of the atmosphere. Thus, the dynamic processes in the mesosphere and thermosphere may strongly influence the intensity of the 5577 Å-emission. On the other hand, the emission is not affected by charged particles.

An increase of the emission intensity was recorded for the time before an earthquake (Fishkova L.M., 1984, Toroshelidze T.I. and Fishkova L.M., 1989, Fishkova L.M. et al., 1985). In five cases the photometric observations at the Abastumani station lasted three nights before the earthquakes. For instance, 5-6 hours before the earthquake of the 24.01.82 ($M = 4.1$, $R = 55$ km, $h = 10$ km) the intensity of the 5577 Å-emission at the zenith was about 2.5 times larger than the mean seasonal value.

The spectral analysis of the 5577 Å-emission oscillations carried out for some special earthquakes using the measurements at the Abastumani station showed an energy increase for the whole interval of periods (from some minutes up to 120 minutes) and an increase of the numbers of the spectral density maximum in the short period range. These variations start some days before an earthquake and approach their maximum value some hours before the shock (Toroshelidze T.I. and Fishkova L.M., 1988).

Comparing the variations of the emission intensity with the parameters of the sporadic E-layer, it was found, that the mean intensity $\{I\}$ is in a good correlation with the $f_b E_s$ frequency (the correlation coefficient was $k = 0.7$ during the studied period, $\delta k = 0.1$). Between the variations of $\{I\}$ and $f_o E_s$, a time interval of the order of one hour was observed.

It will be recalled that $f_o E_s$ depends on the occurrence of small-scale inhomogeneities in the sporadic E-layer density profile. A strong increase of the $f_o E_s$ parameter and the night-time emissions' intensity may be associated with long-periodic (with a period of some hours) internal gravity waves propagating through the ionosphere.

Thus one can assume that long-periodic atmospheric gravity waves (AGW), caused by the earthquake preparation processes, excite mall-scale turbulence in the course of their dissipation. As the result the temperature of the neutral particles changes and the $f_o E_s$-parameter increases. On the other hand, it can be assumed, that short-periodic variations represent infrasonic waves, excited during earthquake preparation, and that the increase of the oscillatory energy is simply a consequence of the enhancement of turbulence due to dissipation processes.

6 Physical models of lithosphere-ionosphere links

6.1 Lithosphere-ionosphere links due to AGW

The model of lithosphere-ionosphere coupling before earthquakes was proposed for the interpretation of recently obtained non-expected results. It turns out that the influence of the earthquake preparation processes on the ionosphere can be detected at the altitude of the E-region at distances of up to 1000 km from the epicentre. The only agent that can be responsible for the formation and density decrease of sporadic layers at such distances may be the acoustic-gravity waves (AGW) of the neutral atmosphere. In this connection, of course, the question of the reason of the formation of AGW in the near-earth layers of the atmosphere occurred.

During the seismological measurements, the stable spectrum of seismo-gravity oscillations, as it is called, with the period from half an hour to four hours was recorded (Lin'kov E.M. et al., 1989, 1990). The theory of such oscillations is not sufficiently developed up to now, but it is known from the experiment that the long-periodic oscillations, with a period more than one hour, can intensificate a few days before strong earthquakes. There is a suggestion, that such oscillations are the eigen-oscillations of the earth. This hypothesis and the planetary theory of oscillations are supported by the fact, that the spectra which were obtained simultaneously near the cities of St. Petersburg and Tbilisi, are identical (between St. Petersburg and Tbilisi, there is a distance of 2200 km).

It should be mentioned, that the experiments show an intensification of both the vertical and horizontal components of the seismo-gravity oscillations. The latter component for instance manifests itself in the fact of intensity modification of the natural electromagnetic emission (EME) in the interval of periods T = 2-3 h before the seismic events (Bella F. et al., 1992). During the observations of seismo-gravity pulsations before strong earthquakes with a magnitude of $M = 6.0$, pulsations with periods from one hour to five hours were found.

During the seismo-gravity oscillations, the earth's surface can act as a piston pushing the atmosphere. Besides the earth's surface oscillations can be able to change the gravitational acceleration, and then the oscillations of the gravitational potential can result in oscillations of the whole atmosphere. The density oscillations in the atmosphere are also registered during quiet periods. These oscillations are coherent with some seismo-gravity modes with frequencies which are close to the frequencies of the atmosphere's eigen-oscillations (Garmash S.V. et al., 1989).

Besides this, AGW may have a meteorological reason. The observations of short-time meteorological precursors in Middle Asia (Mil'kis M.P., 1986) allowed to show variations of the atmospheric pressure, the relative humidity, air temperature and wind velocity during times of earthquake preparation. The phenomena occurred during periods of some hours and up to two days before a number of strong earthquakes. One can assume that the cause of the pressure pulsations are the variations of the earth's surface temperature over a large area.

The density of sporadic E-layers can change up to distances of about 1000 km from the earthquakes' preparation area by influence of AGW with a period of some hours. These AGW are called internal gravity waves.

Variations of the mean night-time density of sporadic E-layers during times of earthquake preparation result, due to AGW, to a decrease of the correlation of the mean night-time frequencies $f_b E_s$ observed by VS-stations situated at distances of some hundred kilometers one from the other.

It should be mentioned, that by propagation of short-time AGW with periods of 30 - 45 min the density of sporadic layers can vary with the same characteristic time.

Let us briefly discuss now the effects of formation and destruction of sporadic layers by the action of AGW.

At moderate altitudes of the order of 90 km to 100 km sporadic layers with moderate density ($n = 10^{10}$ m^{-3}) can form because of the accumulation of less dense layers, which have formed at altitudes of 110-120 km by the action of wind shear created due to the action of AGW (Koren'kov Yu.N., 1979, 1987). Furthermore, the layers move down as a whole with a velocity equal to the phase velocity of the wave. At lower altitudes the zonal component of the neutral wind velocity causes weak vertical motions of the metallic ions.

Thus the layer motion will slow down and stop.

Further, at suitable wave phase of the neutral wind, the neutral gas flux, interacting with the metallic ions, causes a weak upward motion of these ions. As a result the metallic ions feel a certain buoyancy into the direction of the above-lying sporadic layers. Then, the layers merge, and the concentrations of the newly formed layers become somewhat larger than the concentrations of the single layers. Such a mechanism can take place for AGW with periods of 30 to 50 min.

About two days before an earthquake often an appearance and disappearance of weak sporadic layers with densities of $n \approx 10^{10}$ m^{-3} and periods of 30-60 minutes are observed. This is especially well detected in winter and in autumn. In these cases the tracks of the layer on the ionogram appear and disappear with a characteristic time scale also equal to 30-60 min. It should be mentioned, that the larger variability occurs at distances of up to 500 km from the epicentre, which corresponds to the propagation radius of AGW with a period of 0.5 - 1 h.

On the basis of the acoustic-gravity mechanism, the increase of the night-airglow emissions' intensity at wavelength $\lambda = 5577$ Å can be interpreted. During the dissipation of AGW in the E-region the concentration of NO^+ and the temperature increase due to turbulent mixing result in an increase of the emission intensity.

The simultaneous observations of pressure and other meteorological parameters and ionospheric observations in seismoactive regions within a network of stations on the earth's surface would allow to proof the "acoustic" hypothesis of links in the system lithosphere-atmosphere-ionosphere experimentally. But such simultaneous observations have not been performed up to now.

6.2 Electromagnetic models for the lithosphere-ionosphere coupling

Let us examine electromagnetic models for the lithosphere-ionosphere coupling during the time of earthquake preparation. Recently, three possible versions of electromagnetic mechanisms of lithosphere-ionosphere links are discussed.

The first hypothesis is the hypothesis of a "constant" electric field. It should be recalled that the characteristic Maxwell relaxation time is $\tau_o = \varepsilon_o/\sigma_o \approx 15$ min in the atmosphere near the earth's surface, where σ_o is the atmospheric conductivity. It means that if an electrical charge appears on the earth's surface owing to some physical processes, this charge is bound to decrease proportional to $\exp(-t/\tau_o)$, or the source of electrical current must be under the earth's surface. If the hypothesis of the quasi-constant charges and electric fields is supposed, one must keep in mind that the characteristic time-scale of the electric field variations τ is much larger than τ_o.

Thus, the constant local seismic E_L-field hypothesis before an earthquake, from the onset, is not a simple and natural one. But it was used in a number of papers (Morgounov V.A., 1988, Gokhberg M.B., 1995)

According to the models basing on the assumption of quasi-constant electric field E_L, which amounts sometimes to 10^3 V/m, a vertical electric quasi-stationary current I_L may occur in the lower atmosphere near the surface of the earth.

Under the assumption that the size of the effective earthquake preparation area is $S \approx L^2$ km ($L \approx 100$ km) and the conductivity near the earth's surface is $\sigma_o = 0.2 \times 10^{-13}$ $(\Omega \text{ m})^{-1}$, one gets for the current $I_L \approx E_L \sigma_o S \approx 0.2$ A.

Correspondingly, the quasi-stationary current, closed partially in the ionosphere, will cause heating and some other effects. These ionospheric heating effects will modify the structure of the ionosphere, especially if it contains metallic ions.

An interesting version of the "constant electric field" model was proposed in the papers (Martinenko S.T. et al., 1994, Fuks I.M., et al., 1994). According to the model, the increase in the density of charged particles in the ionospheric D and E layers can be qualitatively interpreted basing on the conductivity variations in the lower atmosphere.

Numerous observations of injections of gases and aerosols of tectonic nature containing metals were performed in areas of seismic activity (Pulinets S.A. et al., 1994; Alekseev V.A. et al., 1995). It turned out that weeks and months before earthquakes, the dispersion of the aerosols varies, and the distribution of the metals in the aerosols with respect to the mass number changes. It seems that these changes reflect the development of mechano-chemical processes in the seismic zone during times of earthquake preparation.

The increase in the atmospheric radiation during earthquake preparation leads to an increase of the ions' generation rate, and hence to conductivity variations. An increase in the atmospheric radiation and a 2.5 times larger peak of the radon concentration was observed by Virk et al. (Virk H.S. et al., 1994) about one week before an earthquake. The measurements were performed at an distance of 300 km from the epicenter of the earthquake of the October 20, 1991 in the north of India. In (Heinicke et al., 1995), it was mentioned that five days before an earthquake the radon concentration grew about 4 times. It was also mentioned that the statistical analysis of about 300 microearthquakes ($M < 4$) in the South-East of Germany showed, that in 75 per cent of the cases the earthquakes were preceded by considerable increases in the radon concentration.

In the paper (Pulinets S.A. et al., 1994), it was proposed that a number of geophysical effects of earthquake preparation can be connected with metallic aerosols of tectonic origin. The aerosol ejection at the surface of the earth is caused by piezoelectric fields and microparticles emerging during the core cracking.

Further, models exist, where the earth's ionosphere is conceived as spherical condenser. There it is assumed that the negative charge Q_- is located on the earth's surface, and the positive charge Q_+ is located in the ionosphere. These charges create a potential difference V, and hence a constant atmospheric electric field E_o and, due to the finite conductivity of the atmosphere, a current I_o are observed.

The maintenance of the charge is a sequence of thunderstorms. Due to the good conductivity of the earth and the ionosphere the charge extends over the earth's surface with a time-scale of a few seconds.

The injection of radioactive gases (in particular radon and its products) before an earthquake modifies the distributions of the charges and currents in the coupled atmosphere-ionosphere system. The increase of the concentration of ionisation sources in the lower atmosphere results in an increase of the conductivity. Due to this process, the vertical current connecting the earth and the ionosphere is strengthened. The increase of this current in the ionosphere leads to an increase of its electric field, accordingly also the electron temperature of the ionosphere increases. The heating is connected with a growing electron-neutral collision frequency ν_{en}. Consequently, the conductivity of the ionosphere decreases, and the electric field increases. Such types of ionospheric processes possess characteristic time scales of the charged particles' density modifications of a few hours. In (Sorokin V.M. and Chmyrev V.M., 1998; Chmyrev et al., 1997; Sorokin V.M. and Jashenko A.K., 1998) a detailed theoretical study of the modification of the altitude distribution of the conductivity and the electric field in the system earth-ionosphere is presented. The modification is the result of the increase of the atmospheric radioactivity. During the radioactive decays occur gamma quanta, which are absorbed by the electrons of the molecules of the air due to the Compton effect. The deceleration of fast electrons in the air is accompanied by collisional ionization. The velocity of the generation of ions $q_e(z)$ at the altitude z as result of the ionization by atmospheric radioactivity depends on the particle concentration $n_r(z)$, and may be expressed by a linear integral operator

$$q_e(z) = \frac{\lambda k}{2 l_\gamma(z)} \int\limits_0^\infty dz' n_r(z') E_1[k(z, z')],$$

$$E_1(u) = \int\limits_1^\infty \frac{\exp(-ux)}{x} dx,$$

$$k(z, z') = \frac{H}{l_{\gamma 0}} \left| \exp\left(-\frac{z}{H}\right) - \exp\left(-\frac{z'}{H}\right) \right|$$

where $\lambda = \varepsilon/33$ eV, ε is the energy of the fast electrons, $k = \ln 2/T$, T designates the half-life period, l_γ is the average track length of the gamma quantum, and H represents the atmospheric scale height. The equilibrium concentrations of the generated electrons and ions are determined by the recombination processes in the air. The stationary state of the iono-molecular structure of the ionosphere and its conductivity were determined considering the system of recombination processes of the ions. It was shown that the conductivity of the lower atmospheric layers with a total thickness of several kilometers increases with increasing radiation level near the earth's surface. The altitudinal distribution of the electric field in the system earth-ionosphere may be expressed by

$$E(z) = \frac{E_o(0)\sigma_o(0)}{\sigma(z)} \frac{\int_0^h (dz/\sigma_o(z))}{\int_0^h (dz/\sigma(z))}.$$

Here h is the altitude of the border of the lower atmosphere. The undisturbed electric field E_o corresponds to the average undisturbed conductivity of the atmosphere $\sigma_o(z)$. Due to the additional ejection of radioactive elements before earthquakes, the conductivity becomes $\sigma(z)$. The calculations show that the electric field strength near the earth's surface can increase several times, whereas the electric field strength decreases near the earth's surface due to the conductivity increase.

It should be emphasized that the largest resistance to the electrical currents shows the near-ground lower atmosphere. The conductivity increases as a result of the injection of radioactive elements. And this process leads to a considerable increase of the atmospheric currents and the electric field strengths in the upper part of the system earth-ionosphere.

Modifications of the ionospheric electric fields may lead to dynamical processes in the ionosphere, in particular to the generation of the dissipative instability of the acoustic-gravity waves at the Brünt-Väissälä frequency and to the creation of horizontal periodic inhomogeneities of the ionospheric conductivity (Sorokin V.M. and Chmyrev V.M., 1997; Sorokin V.M., Chmyrev V.M. and Isaev N.V., 1998; Chmyrev V.M. et al., 1998). This instability is connected with the release of Joule heat by disturbed currents during the modification of the ionospheric conductivity by the waves. The release of the Joule heat increases the amplitudes of the atmospheric gravity waves and, hence, the magnitude of the conductivity disturbances, that, in turn, leads to exponential wave growth.

In the mentioned papers, there was underlined, that the Joule heating, due to ionospheric currents in the earthquake preparation region, may contribute the significant part of the heating in the overall heat balance of the ionosphere.

The intensification of atmospheric processes and the increase of the concentration of charged aerosols can cause additional currents in the electric circuit of the atmosphere. This currents then, in turn, may modify the old system of currents and electric fields in the ionosphere. Thus, in the ionosphere above the region of earthquake preparation, locally the strength of the quasistationary transversal electric field may increase a few times. The characteristic space-scale of the disturbed ionospheric region can be a few hundred kilometers Chmyrev V.M. et al., 1998).

Further, in a number of papers the hypothesis of a "series of pulses" was elaborated.

According to it, the action on the ionosphere is provided due to series of electric pulses with characteristic time-scales $\tau_1 = 0.1 - 1$ s (Kolokolov L.E. et al., 1992, Molchanov O.A., 1991). The mentioned characteristic time-scale was found from experimental facts.

It has been established in several studies (see, e.g. Gokhberg M.B. et al., 1995), that the electric field spikes with $\delta E \leq 10^3$ V/m occur in the epicentral zone at day-time a few days before an earthquake. On the other hand, magnetic field variations observed in the same area (regrettably, for different events) showed $\delta B \approx$ 1-10 nT (Liperovsky et al., 1992).

Even without a knowledge of the specific electromagnetic processes in the earth, and treating the earthquake preparation region as a "black box", one can suggest some general hypothesis.

Let us suppose that near the earth's surface a pulse of charge separation (Q-charge) with characteristic time-scale τ_1 is triggered by some factors. We assume that the characteristic spatial scale of the electromagnetic processes is comparable with the earthquake preparation region (i.e. $L \approx 100$ km) for strong earthquakes (magnitude $M \geq$ 4.5-6.5). Then, for the total current $I \approx Q/\tau_1$ we have, and for the electric field near the earth's surface, assuming that the charges are distributed homogeneously on an area $\sim L^2$, we have $\delta E \approx Q/2\varepsilon_o L^2$. For the magnetic field variation, assuming that the current is homogeneously distributed on a flat sheet of size L, we have $\delta B \approx \mu_o I/2L$. These relations yield an estimate for the characteristic time of the process

$$\tau_1 = \varepsilon_o \mu_o L \delta E/\delta B.$$

For accepted δE, δB and L, the characteristic time is $\tau_1 \approx 1$ s, $Q = 200$ C. Note that this estimate involves an extrapolation of observational data of spikes of δE and δB for characteristic experimental device times which are at least an order of magnitude longer. The accuracy of this estimate is low, and one can speak of a characteristic time interval ranging from 0.1 to 10 seconds.

This estimate suggests the possibility of the existence of processes lasting seconds, which should be studied experimentally. Some experimental indications of the existence of electromagnetic activity spikes with such characteristic times are found in a number of papers (Fraser-Smith A.C. et al., 1990; Kopytenko Yu.A. et al., 1993).

For the same simplified model of local charge separation, we can now estimate the local electric field in the ionosphere. This field consists of two components of different origin, the eddy electric field δE^v and the potential field δE^p. The eddy electric field is associated with the variation of the ionospheric magnetic field and can be estimated from the Maxwell equations. For the same parameters $Q = 200$ C, $\tau_1 = 1$ s and $\delta B = 1$ nT we obtain $\delta E^v \approx 10^{-4}$ V/m.

Correspondingly, δE^p can also be of piezomagnetic nature, or it can be produced by resistivity variations caused by a change in the mechanical stress in the presence of lithospheric quasi-constant currents.

We can show, however, that the eddy electric field should be compensated by fields of the screening electric charges of the ionosphere within time-scales $\tau_1 \sim \nu_{en}/\omega_{pe}^2 \sim 10^{-6}$ s, and so it would not have a significant effect.

Within this model of pulse of charge separation with scale $L = 100$ km, one should observe in the ionosphere a creation of induced charges $Q^* \leq Q$, which are similar with respect to characteristic scale and magnitude. Their corresponding field-aligned electric fields $\delta E_{\parallel}^p$ can be evaluated from Ohm's law, $m\nu_{en}\nu_{\parallel} \approx e\delta E_{\parallel}$, and the relation $Q^*/\tau_1 \approx S_{eff}ne\nu_{\parallel}$, where $S_{eff} \approx L^2\beta$. The estimation of the possible electric field in the ionosphere gives

$$\delta E_{\parallel} \leq Q^* m\nu_{en}/\tau_1 L^2 \beta n e^2 \approx 3 \times 10^{-4} \quad \text{V/m},$$

where $L = 10^5$ m, $n = 10^9$ m^{-3}, $\nu_{en} = 4 \times 10^4$ 1/s, $\beta = 0.3 = \cos\alpha$, where α is the tilting angle of the geomagnetic field's force lines.

We now discuss the heating of the ionosphere by the electric fields of seismic origin. The equation for the Joule heating of the ionosphere is

$$\frac{dT_e}{dt} \approx mV_{\parallel}^2\nu_{en} - \delta(T_e - T_n)\nu_{en}$$

where the term proportional to δ is the energy transferred from the electrons to the neutral particles during the collisions (according to (Gurevich A.V., 1978), $\delta = 1.6 \times 10^{-3}$ neglecting inelastic collisions). At times $\tau_1 \approx 1$ s, we can ignore the nonstationary term in this equation. Hence,

$$\Delta T_e \approx mV_{\|}^2/\delta.$$

It is clear that, to explain the anomalous decrease of the density of a sporadic E-layer, we must have $\Delta T_e \approx T_e$. The mentioned conditions correspond to $V_{\|}^* \approx (T_e\delta/m)^{1/2} \approx 3 \times 10^3$ m/s ($T_e = 0.03$ eV), and according to Ohm's law $m\nu_{en}V = e\delta E_{\|}$ and $\delta E_{\|} \approx 7 \times 10^{-4}$ V/m. To realize these longitudinal electric fields, it is necessary to assume several times larger charges, or to assume the process of charge separation to be more quick, e.g. $\tau \approx 0.2 - 0.3$ s. Using for the spreading time of the sporadic layers the expression

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

(where a is the sporadic E-layer thickness, usually $a = 100 - 1000$ m, D is the ambipolar diffusion coefficient, and T_e and T_i are expressed in Joules), one obtains for the life-time of the layer $\tau_D \approx 100$ min, if $a = 500$ m and $D = 60$ m^2/s. For a sporadic layer with thickness of the order of 150 m, the characteristic spreading time should be 15 min., which corresponds to a “cut-off”, that means to a sharp density decrease.

In case of the above chosen parameters, it is significant, that Joule heating is effective in the night-time E-region plasma with $n \approx 4 \times 10^8$ m^{-3}, but the sporadic E-layer can be also heated by thermal conductivity processes. The characteristic thickness of the sporadic layer for which heat conductivity plays an important role is approximately 100 m. The estimations give $k\|T_e/a^2 \approx (T_e - T_i)\nu_{en}$, where $k_{\|} = 3nT_e/m\nu_{in}$ is the heat conductivity along the magnetic force lines.

Thus, from the estimation one can see, that an electric field of seismic origin ($E_L \approx 10^3$ V/m) can intensify the ambipolar diffusion and reduce the characteristic spreading time by tens of per cent during the natural spreading of a “thin” sporadic E-layer. For more noticable heating and intensification of ambipolar diffusion in the maximum of a “thick” sporadic E-layer, e.g. at $f_bE_s = 1.3$ MHz, according to this mechanism, the electric fields on the earth's surface should be 1-1.5 orders stronger.

Finally, we discuss yet one other possible model of electromagnetic coupling in the system litosphere-ionosphere, the so-called "resonance" model (Gokhberg M.B. et al., 1985). This model assumes that the electromagnetic energy transfer from the litosphere to the ionosphere can take place due to the generation of oscillations in a hypothetical resonator in the earthcrust-ionosphere system. Taking the block-structure of the earthcrust into account (Sadovsky M.A., 1979), supposing that for not very strong earthquakes the size of blocks $L \approx H$, where H is the effective distance between the earth's surface and the ionospheric E-layer, one can evaluate the capacity of the litosphere-ionosphere system in the earthquake prediction region by $C \approx \varepsilon_o H.$ and the inductance may be approximated by L$\approx \mu_o H.$ Further one can get the oscillation period $T = 2\pi(\mathrm{L}C)^{1/2} \approx 2\pi H(\varepsilon_o \mu_o)^{1/2}$, and correspondingly $f = 1/T \approx 0.5$ kHz. The possibility of resonance effects was also studied in the papers (Tate J.B., 1989, 1990). At this point, it has to be mentioned, that nowadays, there is no experimental confirmation of the "resonance" model, although VLF electromagnetic emissions were studied for a number of earthquakes (Gokhberg M.B. et al., 1995, Hayakawa M. et al., 1994). There was no observation of strong enough high-frequency electromagnetic disturbances on the basis of which conclusions about an effective coupling could be made. Thus, we believe that resonance effects are not the deciding ones in the litosphere-ionosphere coupling during the period of earthquake preparation.

6.3 Sporadic E-layers as current generators

Let us consider one possible mechanism of the action of acoustic disturbances on a spatially inhomogeneous sporadic E-layer of finite dimensions. One can see, that in this system a three-dimensional complex of electric fields and currents may be generated, which may also excite some instabilities and plasma turbulence.

In the papers (Liperovsky V.A. et al., 1996, 1997, Liperovsky V.A. and Meister C.-V., 1996, Meister C.-V. and Liperovsky V.A., 1996) quasi two- and three-dimensional models of night-time sporadic E-layers as current generator were developed (see figure 4 from (Liperovsky V.A. et al., 1996)). The models seem to be applicable for altitudes between 95 km and 130 km. It was assumed that the layers are situated in the ambient plasma of about fifty times lower density. Under the action of the non-linear wave-form of acoustic disturbances with characteristic time-scales of about 1-5 minutes, generated in the near-earth atmosphere, sporadic E-layers are modified. But for larger periods such a mechanism is not effective enough. Within the proposed model the electron current was closed by the external circuit, for which approximate electrotechnical and magnetohydrodynamical descriptions were developed.

In the quasi two-dimensional model the electrical polarization field was considered and estimated taking into account altitude profiles of the electrical conductivity and heating effects. Further, a three-dimensional current generator model was developed taking into account horizontal dimensions and the difference between the electron and ion currents in the neutral wind direction.

According to the experiment, a system of two flat, horizontal sporadic E-layers, which are located one above the other, is not very rare in the middle atmosphere. So it was possible to elaborate a model of two finite plasma layers. It was assumed, that in the external circuit, generated by the first layer-"generator", also a second sporadic layer-"load" can occur. Thus, currents in two horizontal plasma layers of different density and field-aligned currents connecting the borders of the two layers were considered. Only in the sporadic layer forming the current generator, the existence of a neutral wind was suggested. For the layer-"load" no neutral wind was taken into account. The result of the performed three-dimensional analysis was, that under appropriate geophysical conditions in a system of two thin sporadic layers of moderate density the Hall currents in the layer-"generator" can reach the critical value, when the velocity of the neutral wind is larger than the sound velocity, and the excitation of the Farley-Buneman instability seems to be possible. Besides, if the sporadic layers are rather thick and dense, the field-aligned currents in the external circuit can generate ion-acoustic turbulence.

Thus one can see, that near the epicentric zone of a preparing earthquake the mechanism of seismo-ionospheric coupling may be activated if strong acoustic waves occur before and during the earthquake. This mechanism may lead to plasma turbulence and heating. It is an important fact, that the discussed effects are spatially local, for example, the horizontal scale of the currents may be a few kilometres. The local currents may heat the ionosphere, and this heating may be the reason for the local increase of atmospheric optical emissions with horizontal characteristic scales of some tens of kilometres. The last effect may be applied in satellite seismo-monitoring systems.

7 Discussions and conclusions

A survey of papers on possible links between litosphere, atmosphere and E-region of the ionosphere was given in this paper.

In the study it is shown that ionospheric phenomena due to earthquake preparation processes occurring some days before earthquakes possess different characteristic time-scales and spatial scales.

The spatial scale of seismo-ionospheric effects with characteristic times of some hours is about 1000 km. Up to such distances, a decrease of the correlations between the mean night-time characteristic frequencies $f_b E_s$ at the different sites of observations was registered. This correlations were found by the network of VS-stations situated at distances of some hundreds of kilometres one from the other. Up to such distances, an increase of the number of bay-formed $f_b E_s$ variations with characteristic time-scales of 2-3 hours is observed.

The effects of decrease of the mean night-time frequencies $f_b E_s$ some hours before earthquakes are detected at distances of up to 500 km. Also up to such distances the increase of the intensity of variations with characteristic time-scales of 10-45 min and 2-5 min is found.

That the night-airglow emissions' intensity at wavelength 5577 Å increases was detected at distances of up to 300 km. It should be noted that the intensity of the night-airglow emissions is often correlated with the characteristic frequency $f_o E_s$ of the sporadic E-layer.

The recently discussed models of disturbance-transfer from the litosphere to the ionosphere can be arbitrarily classified in “acoustic-gravity” and “electromagnetic” models.

Let us consider the general possible scheme using Figure 5, which illustrates these two models of influence of earthquake preparation processes on ionospheric E-regions.

On the bottom of the scheme, the processes in the earth are indicated. During the earthquake preparation phase, processes of shifts and compression occur in the earth's crust in the preparation area, and seismo-gravity oscillations with periods from some tenths of minutes and up to some hours are excited.

First, acoustic and acoustic-gravity waves may appear in the near-earth atmosphere due to the earth's ground temperature variations, which occur while the earth's core in the epicentric zone is stressed and its water balance is disturbed, second, due to the seismo-gravity oscillations.

The next floor of the scheme represents the processes at the earth's surface and in the near-earth atmosphere. Here the left part of the scheme demonstrates the electrical and electro-magnetic models, and the right part of the scheme shows the acoustic-gravity models.

The electromagnetic processes at the earth's surface and in the near-earth atmosphere are connected with the separation and motion of the electrical charges due to compression of rocks and the motion of the ground water and gases. And indeed, before earthquakes, pulsing spots of charges were observed at the earth's surface, and corresponding currents were detected in the earth's crust.

It was shown that the generation and modification of the natural electromagnetic emissions takes place during seismoactive periods. Here it should be noted, that the electromagnetic field amplitudes at VLF frequencies observed in the atmosphere before earthquakes are not sufficient to cause modifications of sporadic layers in the ionosphere.

One of the most adequate models considering electrodynamic influences on the ionosphere reduces the number of seismoionospheric effects to an only reason - the modification of the current flowing from the ionosphere to the earth. A few days before an earthquake, the intensity of injection of radioactive gases and charged aerosols grows. As a result the atmospheric electrical field changes, and the structure of the electrical field at E-region altitudes is modified.

On the forth floor of the scheme one can see the description of the processes in the atmosphere at the height of the E-layers.

And on the last, top floor some processes which take place in the ionosphere due to the litospheric changes during the time of earthquake preparation are shown.

The penetration of the quasi-stationary electric field from the earth's surface into the ionosphere belongs to the group of "electromagnetic" processes. If one assumes, that the field possesses a quasi-constant value in the preparation area of a strong earthquake during some hours, then sporadic layers may be generated.

Another possible process is the process of generation of spikes of electric currents. As a result of it the electron temperature in the sporadic E-layers increases, and the density of the sporadic E-layers decreases, and its spread will be more intense. It can provide the intensification of spreading of sporadic E-layers.

Due to the propagation of AGW with long time-scales at latitudes of the E-regions, high-density sporadic E-layers may be generated and exist for a long time under the condition that the period of these AGW are of the order of some hours, and thus the propagation radius of AGW has a value of about 1000 km.

Besides, the sporadic E-layer can also spread under the action of these AGW in dependence on the wave phase.

The quasi three-dimensional model of the sporadic layer as current generator was suggested to understand and to interprete some experimental phenomena. It was shown, that under the action of acoustic waves on a sporadic layer of finite dimension, a local current system in an E-region may be generated. Perpendicular to the geomagnetic field an electric field of the order of 10 mV/m may occur. Then, under the action of the currents, the plasma turbulence, in particular the Farley-Buneman, ion-acoustic and, at altitudes above 130 km, the ion-cyclotron turbulence, may appear.

Dissipation of acoustic and acoustico-gravity waves may cause turbulent mixing in the E-region, variations of the concentrations of the neutrals, of its temperature enhancement, and, besides, causes an increasing airglow intensity at $\lambda = 5577$ Å. Also, turbulization leads to an intensification of the diffusion and to a spread of sporadic E-layers.

In the paper, the usually used model of electromagnetic lithosphere-ionosphere coupling is compared with the acoustic-gravity coupling model. ¿From the authors' point of view, in order to interprete ionospheric phenomena due to earthquake preparation processes, one can use both models. The problem of their consistency with the experiment may be only solved by the analysis of future complex experiments.

Further, it has to be underlined that the mechanisms of the further propagation of disturbances of litospheric origin from the E-region to the F-region are yet unclear. The observed F-region variations have larger space scales than the E-region modifications. Thus, it is necessary to consider the hypotheses of an additional source of free energy in the E-region of the ionosphere to interprete seismic influences on the F-region.

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