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Variability of sporadic E-layer semi transparency $(f_oE_s - f_bE_s)$ with magnitude and distance from earthquake epicenters to vertical sounding stations

E. V. Liperovskaya[1], **O. A. Pokhotelov**[1], **Y. Hobara**[2], **and M. Parrot**[2]

[1]United Institute of Physics of the Earth, 123810 Moscow, Russia
[2]LPCE/CNRS, 45071 Orléans Cedex 2, France

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Abstract. Variations of the E_s-layer semi transparency coefficient were analyzed for more than 100 earthquakes with magnitudes $M > 4$ and depths $h < 100$ km. Data of mid latitude vertical sounding stations (Kokubunji, Akita, and Yamagawa) have been used for several decades before and after earthquake occurrences. The semi-transparency coefficient of E_s-layer $X = (f_oE_s - f_bE_s)/f_bE_s$ can characterize, for thin layers, the presence of small scale plasma turbulence. It is shown that the turbulence level decreases by ∼10% during three days before earthquakes probably due to the heating of the atmosphere. On the contrary, the turbulence level increases by the same value from one to three days after the shocks. For earthquakes with magnitudes $M > 5$ the effect exists at distances up to 300 km from the epicenters. The effect could also exist for weak ($M \sim 4$) and shallow (depth < 50 km) earthquakes at a distance smaller than 200 km from the epicenters.

1 Introduction

More than one decade different researchers have observed the ionospheric disturbances before individual strong earthquakes. On one hand, a future task is now to find regular seismoionospheric effects and to statistically prove them. On the other hand, the search for new effects in night time middle latitude ionosphere has been conducted in recent years.

Seismoionospheric effects in the E-region, especially in E_s-layers, have mostly attracted researchers attention (Liperovsky et al., 1992; Parrot and Mogilevsky, 1989; Ondoh and Hayakawa, 2002). The attention is focused on the fact that the E-region is close to the Earth's surface (its height is 90–140 km), and then, is subject to various physical influence such as acoustic, electromagnetic radiation, etc, coming from this surface.

During the last 70 years the Earth's ionosphere was studied by radio physical methods, the most common one being the vertical ionospheric sounding. Ionospheric data (ionograms) are usually obtained once an hour and their main parameters are presented as tables in special issues of observatory reports and on World Data Centers WEB servers.

Under day-time conditions and at altitudes of E-region, regular E-layers and irregular sporadic E_s-layers may simultaneously exist. During the night time the plasma density of the regular E-layer is normally rather small, and no trace of ionization can be found on the ionograms. In this paper only night-time sporadic E-layers are studied.

Sporadic layers are formed by plasma clouds of metallic ions having small vertical (from a few hundred m to a few km) and large horizontal (50–200 km) dimensions. The formation of sporadic E-layers is often attributed to the occurrence of shear winds. These winds originate at the altitude where the local zonal wind changes its direction from the west to the east, i.e. in the region with a wind shear. In this case, charged particles are piled up into a region where the wind velocity divergence vanishes and a sporadic layer is formed. The spreading of sporadic layer is mainly controlled by ambipolar and turbulent diffusion.

The most important characteristics of the E_s-layers are their blanketing frequencies f_bE_s and critical frequencies f_oE_s. For thick regular E-layer (the thickness is $20 \div 40$ km), f_oE is the critical frequency of the ordinary wave which characterizes the largest electron density (i.e. f_oE is proportional to $\sqrt{n_e}$). For thin sporadic E_s-layers (usually the thickness is smaller than 3 km) f_bE_s is the frequency that characterizes the largest plasma density. This effect was identified in the sixties. Gorbunova and Shved (1984) and Takefu (1989) supposed that f_oE_s is related to the scattering process of radio waves by small scale electron density irregularities in E_s-layers. Using the vertical sounding, Takefu (1989) developed a physical model of reflection from a sporadic layer with small scale irregularities in electron density profile. The model calculation of f_bE_s and f_oE_s were performed for several cases: different shapes of the profile, dif-

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Correspondence to: E. V. Liperovskaya
(liper@uipe-ras.scgis.ru)

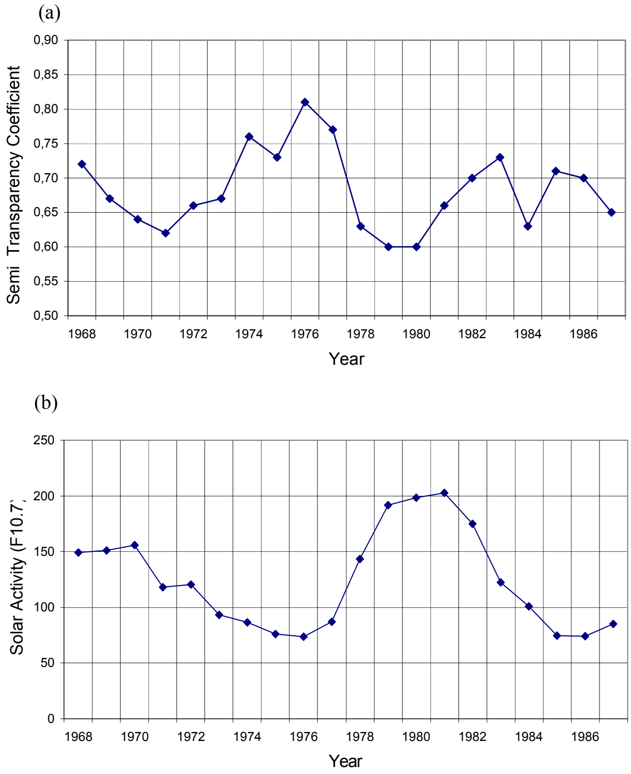

Fig. 1. (a) Yearly dependence of the semi-transparency coefficient of E_s-layer (Yamagawa station), only layers with critical frequencies $f_bE_s < 2.5$ MHz were used in the analysis. **(b)** Annual dependence of F10.7 (solar activity).

ferent scales of irregularities and different sensitivities of the vertical sounding station. Model ionograms calculated for layers with smooth profile and for layers with small scale irregularities were compared. The result was that, if the shape of the profile was slightly disturbed, f_oE_s increases and f_bE_s remains unchanged. Experimental illustrations of theoretical calculations were presented and compared to the results of rocket experiments.

Based on the Takefu conclusions, the variations of the so called semi transparency coefficient $X = (f_oE_s - f_bE_s)/f_bE_s$ is used in the present work as an indicator of variations of small scale electron density irregularities. In order to find ionospheric precursors of earthquakes, the analysis of semi transparency coefficient variations before strong earthquakes and close to vertical sounding stations was carried out.

Another problem is to clarify a mechanism of disturbance transmission from a region of earthquake preparation in the crust to the ionosphere. In the analysis of semi transparency coefficient variations, Liperovsky et al. (1999) noticed that sometimes a foEs variation of $1 \div 2$ MHz occurs in $2 \div 5$ min. To interpret these fast variations, an assumption was made that small scale low frequency turbulence caused by acoustic impulses propagate from the Earth's surface up to ionospheric levels. In the present work, it is also supposed that acoustical mechanism takes place. As it is known, when the temperature of the atmosphere increases, acoustic impulse dissipation increases due to increased absorption. So hypothesis was made that, for less dense (and hence, thin) sporadic layers during solar cycle maximum (the temperature increased), the semi transparency coefficient must be smaller than that during the solar minimum. This assumption was also checked in the present paper.

2 Yearly dependence of E_s-semi transparency coefficient

The analysis of the E_s semi transparency coefficient is carried out using the data of middle latitude vertical sounding stations in Japan, namely Kokubunji, Akita and Yamagawa, from which f_oE_s and f_bE_s data were obtained during 12–20 years.

To avoid direct solar radiation effects during calculation of the averaged value of the semi transparency coefficient, nighttime values were used (20:00–05:00 LT), and besides semi transparency coefficients for low density layers were taken (frequency $f_bE_s < 2.5$ MHz). This frequency was chosen after different attempts in order to demonstrate the effect of the solar cycle. For higher frequencies this effect becomes less significant and for smaller frequencies the number of data points of E_s-layer is not large enough for the analysis of seismoionospheric effects. Data analysis for Japanese stations indicates that the variation of the semi transparency coefficient averaged per year is opposite in phase with the 11-years cycle of solar activity. The yearly dependence of the semi-transparency coefficient for Yamagawa data is shown in Fig. 1a. The yearly dependence of solar activity (F10.7) is shown in Fig. 1b. The negative correlation takes place solely for less dense sporadic layers. This can be interpreted as indirect confirmation of the assumption that small scales irregularities are caused by acoustic impulses from near ground atmosphere.

Similar results were obtained for Kokubunji (1977–1990) and Akita (1977–1988) stations. For all Japanese stations the averaged semi transparency coefficients during solar minimum are 30–40% larger than those for solar maximum.

The analysis of dependence of semi transparency coefficient during the same years was carried out for dense layers ($f_bE_s > 5$ MHz) also, and no dependence on solar activity was found. It is natural to suppose that dense layers are thick layers. For thick layers, f_bE_s does not properly characterize the maximal electron density, and f_oE_s does not characterize the small scale plasma turbulence. Further the layers with small ionization density were only taken into account in the present study (frequency $f_bE_s < 2.5$ MHz).

3 Semi transparency modifications before and after earthquakes

The time dependence of the semi transparency coefficient for a few strong earthquakes ($M \geq 5.5$ and epicenter distance $R < 500$ km) was analyzed by Silina et al. (2001). It was found that the value of the semi-transparency coefficient decreases 1–3 days before deep earthquakes ($H > 33$ km, H is the epicenter depth). Twenty earthquakes were analyzed using the data of Dushanbe (Middle Asia) vertical sounding station. It was interesting to study the effect of semi transparency variations before and after weaker earthquakes ($M < 5.5$) using long-term statistical data for many years. These data of Kokubunji, Akita and Yamagawa stations were used in order to study the seismoionospheric effects. More than 100 earthquakes have been taken into account for the analysis. Only night time data were used, and time interval from 20:00–05:00 LT could be considered as night hours at latitudes $30° - 40°$ throughout all year, i.e. one could have 10-hourly values of semi transparency per night. Data for 6 nights before the earthquake were taken and these nights were indicated accordingly (-6), (-5), (-4), (-3), (-2) and (-1). The night time hours one day before the shock correspond to the hours of (-1) night. So formally if an earthquake takes place at 02:00 a.m., then the hours of 01:00 a.m. of the earthquake day and the hours 02, 03, 04, 05, 20, 21, 22, 23, 24 of the previous day belong to the (-1) night hours. Furthermore, semi transparency coefficients were separately averaged for (-6, -5, -4) and (-3, -2, -1) nights. Thus, for a given earthquake, the maximum number of coefficients is normally 30 in each group before the mean calculation.

Es layer is not always present at night time, besides in summer time sporadic layer could often screen the F-layer and it is impossible to determine its blanketing frequency f_bE_s. So we take the semi transparency coefficient only when this layer exists ($f_oE_s - f_bE_s > 0$), and when the condition $f_bE_s < 2.5$ MHz is satisfied, i.e. when the E_s-layer electron density is not large. All the above mentioned limitations decrease the number of semi transparency coefficients used for averaging. Then only earthquakes with a corresponding number of semi transparency coefficients larger than 10 (from 30 possible) were analyzed for group (-3, -2, -1) and for group (-6, -5, -4). The mean coefficients for the two groups were normalized for each earthquake,

$$X^{\mathrm{norm}}_{-6-5-4} = 2X_{(-6,\,-5,\,-4)}/(X_{(-6,\,-5,\,-4)} + X_{(-3,\,-2,\,-1)})$$
$$X^{\mathrm{norm}}_{-3-2-1} = 2X_{(-3,\,-2,\,-1)}/(X_{(-6,\,-5,\,-4)} + X_{(-3,\,-2,\,-1)}).$$

Then superposed epoch method was used, and normalized averaged coefficients of semi-transparency $\overline{X}^{\mathrm{norm}}_{(-6-5-4)}$ and $\overline{X}^{\mathrm{norm}}_{(-3-2-1)}$ were calculated for different groups of earthquakes and for different stations. The first group consists of earthquakes with magnitudes $M \geq 5.0$ and $H < 100$ km taking place at distance $R < 300$ km from the vertical sounding stations. The second group consists of earthquakes with magnitudes $4.0 \leq M < 5.0$, $R < 200$ km and $H < 50$ km.

To avoid interference between different earthquakes, only data of "isolated in time" earthquakes were analyzed. The earthquake is considered as "isolated in time" if the time interval between it and the next one was more than 7 days in a given region.

If several earthquakes took place one after another within 7 days, only the first one was taken for the analysis when effects before earthquakes were analyzed, while the last earthquake was taken when effects after earthquakes were analyzed. Such method of earthquakes selections is not fully correct because sometimes foreshocks and aftershocks were used and the main shocks were not used in the analysis. However this method allowed to exclude subjective factor in the analysis of seismoionospheric effects.

The result was that $\overline{X}^{\mathrm{norm}}_{(-3-2-1)}$ was less than $\overline{X}^{\mathrm{norm}}_{(-6-5-4)}$ by few percents for every station, i.e. it seems to be that semi transparency slightly decreased 1–3 days before earthquakes. The effect was weak enough, the decreasing value is much less than the standard deviation calculated for a set of earthquakes. (The values of this standard deviation are about 0.20 for all groups of earthquakes). A question then arose: what was the probability P of the fact that this effect was not casual?

To answer to this question, one should calculate P_{casual} as the probability of the fact that this effect was casual. If this probability is small enough, for example $P_{\mathrm{casual}} < 0.05$, hence the effect is not casual with a probability $P = 1 - P_{\mathrm{casual}}$, i.e. with $P > 0.95$. Then the effect could be treated as seismoionospheric effect.

A study of variations of the ionospheric parameters with a random background process model was performed to evaluate P_{casual}.

To examine this problem, a background random process was constructed in order to find k series with N_{total} virtual events ("virtual earthquakes") in each series using the long time series of the X^{norm} values. To obtain a proper accuracy the value of k must be not less than 1000.

The 6-days time interval was considered before each of these virtual events, $X^{\mathrm{norm}}_{(-6-5-4)}$ and $X^{\mathrm{norm}}_{(-3-2-1)}$ values for two parts of these time intervals were obtained, and after $\overline{X}^{\mathrm{norm}}_{(-6-5-4)}$ and $\overline{X}^{\mathrm{norm}}_{(-3-2-1)}$ were calculated for each series in the similar manner as it was done in the case of the real earthquakes.

Mean $\overline{X}^{\mathrm{norm}}_{(-6-5-4)}$ and $\overline{X}^{\mathrm{norm}}_{(-3-2-1)}$ values for virtual events were distributed in accordance to normal law, and we could obtain the standard deviation σ_X calculated from the k series. The mean value of this normal distribution was equal to 1 (in accordance with the suggested stationarity).

The probability of a random exceeding of the obtained deviation in the X-values occurring in 3-days interval before the real earthquakes was calculated by comparison with the background distribution obtained for the virtual events.

To get this probability we take the discrepancy $(1 - \overline{X}^{\mathrm{norm}}_{(-3-2-1)})/\sigma_X)$ and find probability using normal distribution. The value $\overline{X}^{\mathrm{norm}}_{(-3-2-1)}$ is taken for real earthquakes, the value σ_X was calculated using the random procedure necessary to obtain the k series.

The random deviation for a number of several data sets (corresponding to data sets from different observatories) have been obtained using a random procedure. The number of virtual events was equal N_{total} and all 4 stations were used.

The seismoionospheric effects before earthquakes are shown in Tables 1 and 3; effects after earthquakes are shown

Table 1. The modifications of the averaged normalized coefficient of semi transparency for different stations before earthquakes. The columns, marked as ($N_{(-6,\,-5,\,-4)}$), and ($N_{(-3,\,-2,\,-1)}$) mean the number of earthquakes, for which the semi transparency coefficients in (−6, −5, −4) nights was greater than in the (−3, −2, −1) nights. In the next two columns marked as ($\overline{X}^{\text{norm}}_{(-6,\,-5,\,-4)}$) and ($\overline{X}^{\text{norm}}_{(-3,\,-2,\,-1)}$), the normalized coefficients of semi transparency averaged per group of earthquakes are represented. The values were obtained by the superposed epoch method. The next column contains the mean deviations (σ_X), that were obtained by a random procedure. Last column represents the probability (P_{casual}) of the fact that the decreasing of the semi transparency coefficient is casual. The line "total" represents this probability for all stations together

$M < 5.0$, $R < 300$ km, $H < 100$ km	$N_{(-6,\,-5,\,-4)}$	$N_{(-3,\,-2,\,-1)}$	$\overline{X}^{\text{norm}}_{(-6,\,-5,\,-4)}$	$\overline{X}^{\text{norm}}_{(-3,\,-2,\,-1)}$	σ_X	P_{casual}
Kokubunji	27	10	1.070	0.930	0.038	0.035
Akita	20	11	1.038	0.962	0.043	0.19
Yamagawa	4	3	1.046	0.954	0.090	0.31
Total	51	24	1.054	0.946	0.024	0.025

Table 2. This table represents the results for the time after earthquakes: (−3, −2, −1) nights were compared to (+1, +2, +3) nights

$M < 5.0$, $R < 300$ km, $H < 100$ km	$N_{(-3,\,-2,\,-1)}$	$N_{(+1,\,+2,\,+3)}$	$\overline{X}^{\text{norm}}_{(-3,\,-2,\,-1)}$	$\overline{X}^{\text{norm}}_{(+1,\,+2,\,+3)}$	σ_X	P_{casual}
Kokubunji	18	27	0.954	1.046	0.033	0.08
Akita & Yamagawa	15	22	0.980	1.020	0.041	0.31
Total	33	49	0.966	1.034	0.022	0.07

in Table 2. When we analyzed effects before earthquakes, we compare the semi transparency coefficients in (−6, −5, −4) and (−3, −2, −1) nights; when we analyze effects after earthquakes, we compare the semi transparency coefficients in (−3, −2, −1) and (+1, +2, +3) nights.

The first two columns represent the number of earthquakes used in the analysis. Table column marked as ($N_{(-6,\,-5,\,-4)}$) represents the number of earthquakes for which the semi transparency coefficients in (−6, −5, −4) nights were greater than in (−1, −2, −3) nights, and column marked as ($N_{(-3,\,-2,\,-1)}$) means the number of earthquakes for which the semi transparency coefficients in (−3, −2, −1) nights were greater than in (−6, −5, −4) nights. The total number of earthquakes in consideration is ($N_{(-6,\,-5,\,-4)}$) + ($N_{(-3,\,-2,\,-1)}$). One could see that the semi-transparency coefficients are smaller in (−3, −2, −1) nights for the majority of earthquakes. The next two columns show the normalized semi-transparency coefficients averaged per group of earthquakes marked as $\overline{X}^{\text{norm}}_{(-6-5-4)}$ and $\overline{X}^{\text{norm}}_{(-3-2-1)}$. These values were obtained from the superposed epoch method. The next column contains the mean deviation σ_X. This value was calculated by using a set of random cases from the available data. The last column, marked as (P_{casual}) means the probability that increasing is casual.

The last line of the table represents the total result for all vertical sounding stations. The probability P_{casual} in this line is a probability for all stations, the values in columns $\overline{X}^{\text{norm}}_{(-6-5-4)}$ and $\overline{X}^{\text{norm}}_{(-3-2-1)}$ are averaged results for all stations. The number of data in each station is not enough to make statistically proved conclusion, because normally the condition $(1 - P_{\text{casual}}) > 0.95$ is desirable, but the total result was casual with a probability smaller than 0.025. In this case decreasing of the semi transparency coefficient 1–3 days before earthquakes is not casual with a probability more than $(1 - P_{\text{casual}}) = 0.975$ (real P_{casual} for all stations is less than values in the tables, because we have close effects for each station separately).

The difference between semi transparency coefficients in (−6, −5, −4) and (−3, −2, −1) nights is about 10%. As it was mentioned above, the difference between the coefficients in the minimum and the maximum of the 11 years solar cycle is about 30–40%.

The results for the time after earthquakes are presented in Table 2. One could assume that the heating stopped after earthquakes, but in fact the processes in the Earth before aftershocks could be the same as the processes before main shocks, so heating could continue and the increasing of semi transparency after earthquakes is not so significant comparing with the case of decreasing before earthquakes. The calculated probability of the effect being casual equals to 0.07; in other words, the heating stopped with a probability of 0.93.

The preliminary results before earthquakes with magnitude $4.0 \leq M < 5.0$, $R < 200$ km, $H < 50$ km are presented in Table 3. The probability that increasing takes place before weak earthquakes is equal to $(1 - P) = 0.97$ (Table 3). The available data points are not large enough to make statistically proved conclusion but one could assume that the semi transparency decreasing depends on magnitude and R.

Table 3. The modifications of the averaged normalized coefficient of semi transparency for different stations before earthquakes. The columns, marked as ($N_{(-6,\,-5,\,-4)}$), and ($N_{(-3,\,-2,\,-1)}$) mean the number of earthquakes, for which the semi transparency coefficients in $(-6, -5, -4)$ nights was greater than in the $(-3, -2, -1)$ nights. In the next two columns marked as ($\overline{X}^{\text{norm}}_{(-6,\,-5,\,-4)}$) and ($\overline{X}^{\text{norm}}_{(-3,\,-2,\,-1)}$), the normalized coefficients of semi transparency averaged per group of earthquakes are represented. The values were obtained by the superposed epoch method. The next column contains the mean deviations (σ_X), that were obtained by a random procedure. Last column represents the probability (P_{casual}) of the fact that the decreasing of the semi transparency coefficient is casual. The line "total" represents this probability for all stations together

$4 \le M < 5.0$, $R < 200$ km, $H < 50$ km	$N_{(-6,\,-5,\,-4)}$	$N_{(-3,\,-2,\,-1)}$	$\overline{X}^{\text{norm}}_{(-6,\,-5,\,-4)}$	$\overline{X}^{\text{norm}}_{(-3,\,-2,\,-1)}$	σ_X	P_{casual}
Kokubunji	15	6	1.119	0.881	0.050	0.01
Akita & Yamagawa	7	5	1.021	0.979	0.069	0.38
Total	22	11	1.084	0.916	0.040	0.025

4 Discussion and conclusions

Now the new results of the present work will be discussed in connection to possible interpretation on the basis of physical mechanisms of lithosphere-ionosphere coupling, that were proposed in literature.

Using vertical sounding stations, it was shown that the semi transparency coefficients of the E_s-layers decreased 1–3 days before and increased 1-3 days after earthquakes with magnitudes $M > 5$, depths $H < 100$ km and $R < 300$ km. We also obtain preliminary results showing that the semi transparency coefficient decreased before earthquakes with magnitudes $M > 4$ depths $H < 50$ km and $R < 200$ km. Only not dense layers were taken into account (frequency $f_bE_s < 2.5$ MHz) when we calculate the coefficients of semi transparency.

According to Takefu (1989) and Gorbunova and Shved (1984), the semi transparency coefficient characterizes the existence of small scale inhomogeneities of electron concentration in the sporadic layers, or in other words, the level of small scale wave turbulence of the ionospheric plasma. The decreasing of the semi transparency coefficient allows to suppose that, 1–3 days before earthquakes, heating takes place in the ionosphere that decreases the level of turbulence due to the increasing of diffusion.

What can be the origin of this heating? Two possible mechanisms of disturbances transmission from the region of earthquake preparation in the crust to ionospheric E-region have been already discussed by Liperovsky et al. (2000), Gokhberg and Shalimov (1996), and Sorokin et al. (1998). The first one is the so called "acoustic" mechanism when it was supposed that, in the region of earthquake preparation, low frequency acoustic noise ($f = 0.01 \div 1$ Hz) is generated. Amplitudes of acoustic waves increase when they propagate up to altitudes larger than 100 km and, in sporadic layers, generation of local electrical fields and currents induce heating due to collisions between ions and neutrals (Liperovsky et al., 1997; Haldoupis et al., 1997).

Another mechanism refers to the so called "electrical" one. In this case it is supposed that a few days before earthquakes, local atmospheric electric fields of lithosphere origin arise, change electric field at altitudes up to 100 km, and generate corresponding local electric currents, caused heating in E-region (Gokhberg et al., 1995; Sorokin et al., 1998; Kim and Hegai, 1985). One could suppose that, under specific conditions, ionospheric effects were caused by one of these mechanisms, and in other conditions they were caused by other mechanism. In both cases, local generation of electric fields and local current systems lead to the heating and to the decrease in the semi transparency coefficient due to sufficient decreasing of f_oE_s (while f_bE_s does not change or changes a little).

Let us compare the results of the present work with the results of Silina et al. (2001). In this paper, a small decreasing of the semi transparency coefficient was also revealed for 20 strong ($M \ge 5.5$) and deep $H > 33$ km earthquakes at distances $R < 500$ km. However for strong ($M \ge 5.5$) earthquakes occurring close to the Earth's surface ($H = 3 \div 5$ km), on the contrary a significant increasing of the semi transparency coefficient was revealed. This points out at another mechanism of generation of disturbances in the ionosphere. It must be emphasized that in Silina et al. (2001) there were no limitations on f_bE_s, i.e. coefficients for both dense and not dense layers were used in the analysis. Probably for strong earthquakes close to the Earth's surface the more intensive generation of inhomogeneities in E-region was caused by drift gradient instability, which has a threshold, as it is well known. Only very strong earthquakes close to the surface can generate sufficient spikes of electric fields, and then could trigger this instability.

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