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On ionospheric precursors of earthquakes in scales of 2–3 h

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Abstract

The probability of 2–3 h variation in electron concentration at different regions of ionosphere 1–3 days before earthquakes at distances $R < 500$ km from vertical sounding stations was analyzed. Using 12 months of data sampled each 15 min at one ionospheric station it was revealed that before earthquakes with $M > 4.5$ the number of variations with time scales of 2–3 h in the lower F-layer of the ionosphere f300 (real altitude of about 250 km; virtual altitude of 300 km) increases for 10 earthquakes, decreases for 4 and it does not changes for 2, on 16 cases we analyzed. Using the hourly data of 10 ionospheric stations collected for 20–30 years it was revealed that the number of disturbances in the foF2-frequency (real altitudes of about 300–350 km corresponding to the maximal electron density of F2 layer) with time scales of 2–3 h does not change before earthquakes with $M \leqslant 5.5$ and slightly decreases (on 9%) before more strong earthquakes ($M > 5.5$). Possible models able to justify the phenomenology we observed are presented.

Keywords: Ionosphere; Short-term; Anomalies; Earthquakes

1. Introduction

Ionospheric disturbances with scales of 2–3 h in F, D and E regions of the ionosphere a few days before earthquakes were presented in several papers (Liperovsky et al., 1990, 1997, 1999, 2000; Gaivoronskaya and Zelenova, 1991; Popov et al., 1996; Sharadze et al., 1991).

The application of the usual spectral analysis methods to phenomena connected with the earthquake preparation processes suggests the existence of periodic processes. But, as the studied disturbances may be non-periodic (bay-formed) and as in real data lacks exist which have to be extrapolated, the variability of natural processes is badly represented within standard spectral analysis. In this connection Bella et al. (1992) and Popov et al. (1996) proposed to search for bay-formed disturbances in the temporal behavior of the physical parameters. Disturbances were considered to be bay-formed, if they started with a strong increase (or decrease) of a parameter followed by an interval of almost constant value of the parameter and a rapid decrease (or increase) to the initial value.

Analyzing the daily modifications of the intensity envelope of the electromagnetic signal with frequency 10 MHz propagating along the route Washington–Huancayo, bay-formed disturbances of the D-region lasting 2–3 h before the 1960 Chilean earthquake were pointed out (see for example Gokhberg et al., 1995). The route was approximately along the meridian. The coordinates of Washington are: geographic (38.7°N, 77.1°W), geomagnetic (50.1, 350.7); the coordinates of Huancayo are: geographic (12.0°S, 75.2°W), geomagnetic (−0.1, 353.8).

Liperovsky et al. (1990) studied the influence of earthquakes preparation on the ionosphere and analyzed variations of the critical frequency of the ionosphere f300 at a virtual 300 km altitude. On the basis of the two years data collected at the ionospheric station of Dushanbe, the 2–3 h bay-formed disturbances were growing 1.5–2 times about 1–2 days before earthquakes.

Further, phenomena in the E-region for the sporadic E-layers with characteristic time scales of 0.5–3 h were

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presented by Liperovsky et al. (1999) using the data of the same Dushanbe station. Sporadic layers are formed by plasma clouds of metallic ions having small vertical (from a few hundred meters to a few kilometer) and large horizontal (50–200 km) dimensions. The formation of sporadic E-layers is caused by the occurrence of shear winds, 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 (Whitehead, 1989; Mathews, 1998).

One of the most important characteristics of the Es layers is a blanketing frequency *fbEs*. For thin sporadic Es layers (usually the thickness is smaller than 3 km) fbEs is the frequency that characterizes the largest electron density (i.e. fbEs is proportional to $\sqrt{n_e}$). This effect was identified in the 1960 and a physical model to calculate this case was proposed by Takefu (1989). A bay-formed variations in fbEs may be connected with a spotted structure of horizontally moving clouds of a sporadic layer (Liperovsky et al., 2000).

At the purpose to reveal effects of the seismic activity, the numbers of bay-formed disturbances in fbEs temporary run during seismo-active and background times were compared. For earthquakes with magnitudes $M > 5.0$ a tendency of an increase of the number of 2–3 h bay-formed disturbances of the fbEs-frequency was found 1–2 days before the events.

In further investigations some authors revealed an increase of variations of the foF2-frequency with time scales of 2–3 h at the altitude of the maximum electron density in the F-layer. In this connection it must be mentioned that the critical frequency foF2, corresponding to the maximum of the plasma concentration, is easily measured even with the old low sensitive ionosounds and satellites (Pulinets, 1998).

Thus, analyzing the data of the Tbilisi sounding station for the Spitak earthquake of 1988, an intensification of the 2–3 h variations was found in the spectrum of the frequency foF2 a few days before the event (Sharadze et al., 1991).

Studying the temporal behavior of the frequency foF2 before three earthquakes using the spectral analysis, Gaivoronskaya and Zelenova (1991) also obtained an increase of the amplitudes of the harmonics with periods of 2–3 h.

In all the previous works, data were used which were obtained by standard vertical sounding every 15 min. Note that relatively short periods of time were considered, lasting several days and up to one year. Thus for the foF2-frequency, the increasing of the number of 2–3 h variations was demonstrated only before a limited number of earthquakes.

In this paper a comparative analysis of the bay-formed variations of foF2 and of f300 with duration of 2–3 h was performed for 16 earthquakes using 15 min sampled data. Then a detailed analysis of the foF2 bay-formed variations related to some hundred earthquakes, using the hourly sampled data for 20–30 years at different stations, was carried out.

2. Bay-formed disturbances in f300 and in foF2 ionospheric frequencies

The analysis of the bay-formed disturbances in the F2-ionospheric layer was performed using the 15 min data obtained by the vertical sounding station of Dushanbe (for the coordinates see Table 1). The data of six winter months (from October to March) both in 1986 and in 1987 were available. The number of bay-formed disturbances of the characteristic frequencies f300 and foF2 with durations of 2–3 h in the six nights before earthquakes was studied. An algorithm of identification of bay-formed variation in fof2 and f300 was determined as in Popov et al. (1996). In Fig. 1 an example of a bay-formed disturbance of f300 is presented. The variation from 5 to 13 points (from 23.00 to 01.00) is a bay-formed disturbance; its depth is $H = \frac{h_6+h_7+\cdots+h_{12}}{7}$ and its length is 2 h.

Table 1
Geographic and geomagnetic coordinates of the ionospheric stations and the relative period of observation used in this study

Station	Latitude geographic (°N)	Longitude geographic (°E)	Latitude geomagnetic	Longitude geomagnetic	Period of observation
Akita	39.7	140.1	29.5	205.9	1964–1988
Kokubunji	35.7	139.5	29.5	205.8	1964–1990
Wakkanai	45.4	141.7	35.3	206.5	1964–1988
Yamagawa	31.2	130.6	20.4	198.3	1964–1988
Alma-Ata	43.3	76.9	33.4	151.1	1964–1989
Ashkhabad	37.9	58.3	30.4	133.7	1964–1996
Dushanbe	38.6	68.8	29.7	143.2	1986–1987
Tashkent	41.3	69.6	32.3	144.4	1964–1996
Tbilisi	41.7	44.8	36.2	122.5	1964–1986
Gibilmanna	38.0	14.0	38.1	93.6	1977–1993
Rome	41.9	12.5	42.5	92.4	1977–1995

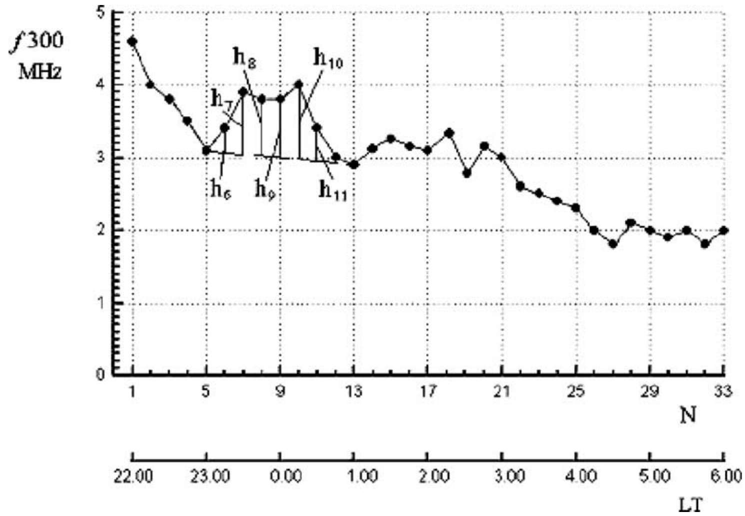

Fig. 1. An example of bay-formed variation in f300 ionospheric layer. The night-time hours (22.00–06.00 LT) correspond to (1–33) number of measurements (each 15 min). The depth of the bay is $H = \frac{h_6+h_7+\cdots+h_{12}}{7}$ and its length is 2 h.

The accuracy of measurement of foF2 and f300 is 0.1 MHz. The mean value of depth of bays is 0.15 MHz for f300 and 0.19 MHz for foF2. We chose 0.2 MHz as the threshold of the minimal depth of a bay for evaluating the variations of number of bays in connection with earthquakes. Night-time measurements were considered for excluding the influence of the solar emissions. It seemed reasonable to assume a 12 h duration for the nights from October to March. The day of earthquake (LT) was considered as 0 day; the days before as −1, −2 and so on. The nights before the earthquakes were divided into two groups: the −6, −5 and −4 nights considered as "background" nights and the −3, −2 and −1 nights considered as "seismo-active" nights. This choice was mainly based on the past results. In fact, several papers summarized in Gokhberg et al. (1995) and Liperovsky et al. (1992, 2000) report that the most part of seismo-ionospheric effects was observed 2–3 days before the earthquake. We did not consider the days after the shock as "background" ones because in these days aftershocks generally happen and so we have not pure background. We take an isolated event in time events; that is, only earthquakes were considered for which the 6 days before the event did not belong to the 6-days period before another earthquake. If a few 6-days periods overlapped (i.e. a series of earthquakes occurred) only the first earthquake was taken into account.

During 12 month data we can pick up only 16 earthquakes with magnitude $M > 4.5$ and distance $R < 500$ from the sounding station, that were "isolated".

An increase of the number of bay-formed disturbances of f300 during the seismo-active nights was observed for 10 of the earthquakes, for four earthquakes this number decreased, and in two cases the number of bay-formed disturbances during the seismo-active nights was equal to the number during the background nights. For these 16 earthquakes the number of bays in the temporary run of f300 was 116 in seismo-active time, while the number of bays in background time was 83. Hence for these 16 earthquakes the mean number of bay-formed disturbances per night at seismo-active time was about 1.4 times larger than the number of bay-formed disturbances at background nights. These results are similar to the results reported in Liperovsky et al. (1990).

For the critical frequency foF2 an increase of the number of the bay-formed disturbances during seismo-active time was obtained for five earthquakes, a decrease was found for six earthquakes, and for five events no changes occurred. So, it seems that none seismo effect exists for the frequency foF2.

A further investigation was carried out for the frequency foF2 analyzing the data registered hourly for several years at 10 vertical sounding stations. These data exist in INTERNET. The coordinates of the stations we used and the observation periods are listed in Table 1.

For estimating the number of bay-formed variations with duration of 2 h, a simplified method was used according to which the value of the depth of the bay-formed disturbance corresponding to every value of the frequency foF2 (further designated by f_i) is: $H_{fi} = |f_i - (f_{i-1} + f_{i+1})/2|$ where f_{i-1}, f_i, f_{i+1} are three successive (with an interval of 1 h) values of the temporary dependence of frequency foF2.

Previously, we used the number of bays per night. Here we estimate a value of bay for each point, each measurement of foF2. The mean value of the bay was equal to 0.19 MHz and the mean value to 0.15 MHz (for all years). For the analysis, only bay-formed variations with a depth of $H_{fi} > 0.2$ MHz were chosen. To avoid the effect of the solar radiation only the night-time data

(i corresponds hours from 21 to 04 h LT) were used. Thus the maximal number of points per night was 8. Of course, if a part of data was absent, this number was smaller.

Further, a value W that could be named "the probability of 2 h variation with the depth more than threshold per one point" was introduced. W represents the ratio of the number of variations with depth $H_{fi} > 0.2$ MHz to the number of points, in which the variations could exist. Obviously to get the 2 h variation in the point i, the values in the $(i-1)$ and $(i+1)$ points must be available.

The W values in the (−6,−5,−4) and (−3,−2,−1) nights before an earthquake were compared to find a possible seismo-ionospheric effect. Only the earthquakes were considered for which the 6 days before the event did not belong to the 6-days period before an another earthquake. If a series of earthquakes occurred within 6 days, only the first earthquake was taken into account. Moreover, for analyzing the earthquakes with $M > 5.5$, at first we chose the earthquakes with $M > 5$ which are isolated in time series and then from this set we pick up the earthquakes with $M > 5.5$. When we analyzed the earthquakes with $M > 5$, the procedure was analogous.

The W values were calculated per two equal time intervals: we got $W_{(-3-2-1)}$ as the probability of 2–3 h variation per point in the (−3,−2,−1) days before the shock and we got $W_{(-6-5-4)}$ as the probability for the (−6,−5,−4) days. Six days intervals were analyzed only if for each 3-days interval there were not less than one/half of possible data.

At the purpose to reveal a possible seismic effect the previous probabilities were compared. At this purpose the value $\Delta W^{\text{norm}} = 2 \cdot (W_{(-3-2-1)} - W_{(-6-5-4)})/(W_{(-3-2-1)} + W_{(-6-5-4)})$ was introduced. This value characterized the modifications of the probability of 2–3 h variations from the (−3,−2,−1) nights to the (−6,−5,−4) nights. If $\Delta W^{\text{norm}} > 0$ it means that the probability of 2–3 h variations increases for the (−3,−2,−1) nights; if $\Delta W^{\text{norm}} < 0$ this probability decreases. The results we obtained are presented in Tables 2–4. From Tables 2–4, it is possible to see that the number of 2–3 h variations is quite equal for earthquakes with magnitudes $4.5 < M \leqslant 5.0$, it decreases a little for earthquakes with magnitudes $5.0 < M \leqslant 5.5$

Table 2
Earthquakes with $M \geqslant 5.5$

Station	$W^{\text{norm}}_{\text{mean}}$ (%)	$N_{(-6-5-4)}$	$N_{(-3-2-1)}$	$N_{=}$	N_{total}
Akita	−0.173	25	18	2	45
Kokubunji	−0.066	35	22	6	63
Wakkanai	−0.152	23	14	2	39
Yamagawa	0.0745	8	15	1	24
Alma-Ata	−0.135	3	3	1	7
Tashkent	−0.011	6	5	1	12
Ashkhabad	0.143	1	2	0	3
Gibilmanna	−0.343	2	0	0	2
Rome	0.028	2	2	0	4
Total	−0.087	105	81	13	199

$W^{\text{norm}}_{\text{mean}}$ (%) is the value of the difference between characteristics of probabilities in the (−3,−2,−1) nights and in the (−6,−5,−4) nights.
$N_{(-6-5-4)}$ is the number of earthquakes for which the probability of 2 h variations in foF2 was more in the (−6,−5,−4) days than in the (−3,−2,−1) days.
$N_{(-3-2-1)}$ is the number of earthquakes for which probability of 2 h variations in foF2 was more in the (−3,−2,−1) days than in the (−6,−5,−4) days.
$N_{=}$ is the number of earthquake for which the previous probabilities were the same.
N_{total} is the total number of events $[N_{\text{total}} = N_{(-6-5-4)}) + N_{(-3-2-1)} + N_{=}]$.

Table 3
Earthquakes with $5.0 \leqslant M < 5.5$

Stations	$W^{\text{norm}}_{\text{mean}}$ (%)	$N_{(-6-5-4)}$	$N_{(-3-2-1)}$	$N_{=}$	N_{total}
Akita	0.006	85	80	10	175
Kokubunji	−0.006	105	86	12	203
Wakkanai	0.036	63	67	2	132
Yamagawa	0.007	42	35	6	83
Alma-Ata	−0.075	27	21	4	52
Tashkent	−0.022	29	31	7	67
Ashkhabad	−0.001	8	9	1	18
Tbilisi	−0.058	9	6	1	16
Gibilmanna	−0.343	2	0	0	2
Rome	0.028	2	2	0	4
Total	−0.001	384	350	46	780

For the meaning of the symbols see the specifications in Table 2.

Table 4
Earthquakes with $4.5 \leqslant M < 5.0$

Stations	$W^{\text{norm}}_{\text{mean}}$ (%)	$N_{(-6-5-4)}$	$N_{(-3-2-1)}$	$N_{=}$	N_{total}
Akita	−0.052	89	85	15	189
Kokubunji	0.007	103	111	19	233
Wakkanai	0.014	95	95	10	200
Yamagawa	0.046	64	72	9	145
Alma-Ata	0.055	61	74	7	142
Tashkent	−0.030	116	92	11	219
Ashkhabad	−0.147	29	19	2	50
Tbilisi	−0.064	22	23	2	47
Gibilmanna	−0.017	6	10	0	16
Rome	0.017	26	27	9	62
Total	0.004	589	585	82	1256

For the meaning of the symbols see the specifications in Table 2.

and it decreases more significant for earthquakes with $M > 5.5$.

Further the mean value of ΔW^{norm} for all the 199 earthquakes we considered was calculated and we obtained $W^{\text{norm}}_{\text{mean}} = -0.09$. The effect we mentioned above is weak enough. The values of the decreasing we pointed out are much less the standard deviation calculated for the set of the earthquakes. So, we investigated the probability P that the previous effect was not casual.

A study of variations of the ionospheric parameters using the random background process model was performed to evaluate the probability P.

To construct the background process, 1000 series with $N_{\text{total}} = 199$ virtual events (earthquakes) in each series were chosen using a random number generator. For each series we calculate the $W^{\text{norm}}_{\text{mean}}$ value, thus obtaining 1000 such values. These 1000 $W^{\text{norm}}_{\text{mean}}$ values were distributed in accordance to a normal distribution and the standard deviation σ_X was calculated. By comparison the σ_X value and the experimental mean value $W^{\text{norm}}_{\text{mean}}$ ($W^{\text{norm}}_{\text{mean}} = 2.5\sigma_X$) (Liperovskaya et al., 2003), it was obtained that the decreasing of the number of the 2–3 h foF2 variations 1–3 days before earthquake took place with $P > 0.98$.

3. Discussion

Variations of the ionospheric frequency f300 were analyzed by Liperovsky et al. (1990) using the data of the Dushanbe station. For a time interval of 12 months, the number and the duration of the bay-formed variations were studied. The results showed that the number of bay-formed variations with duration of 2–3 h increases about 1.5–2 times 1–3 days before earthquakes with magnitudes $M > 5$ and $R < 500$ km from epicenter to ionospheric station in comparison with the background time.

Analogous investigations were performed for the envelope of the intensity of the high-frequency electromagnetic noise, which was registered in a cave in Italy (Bella et al., 1992; Liperovsky et al., 1997) before some earthquakes. Investigating the ratio of the number of bay-formed variations of the envelope of the low-frequency electromagnetic noise during the seismo-active time (equal to 2 days before the shock) to the number of the bay-formed variations during the background time, we concluded that the number of 2–3 h variations also increased about 1.5–2 times.

Bay-formed temporal disturbances for the frequency fbEs of sporadic layers of the ionosphere were investigated by Liperovsky et al. (1999). For earthquakes with $M \geqslant 5.0$ and distance $R < 1000$ km, an increase of the number of bay-formed disturbances of fbEs with duration of 2–3 h in the nights −2 and −1 before earthquakes was shown in comparison with the background nights.

In this research, the analysis of ionospheric disturbances with time scales of 2–3 h at 300 km effective height and at the height of F2 maximal density revealed that there is an increase of the number of bay-formed disturbances at effective 300 km height, but at the height of F2-layer maximum the number of 2–3 h variations does not increased. Moreover, a weak decreasing of these variations is observed statistically.

Possible transport mechanisms of the disturbances from the region of earthquake preparation up to the ionosphere are presented in Miyaki et al. (2002), Molchanov and Hayakawa (1998), Pokhotelov et al. (1995), Mareev et al. (2002), Pulinets et al. (2002), Popov et al. (2002), Ondoh and Hayakawa (2002), and Shalimov and Gokhberg (1998).

Here, we can try to justify the phenomenology we observed. A few days before an earthquake, due to an intensification of the seismo-gravity oscillations (Lin'kov et al., 1990) in the Earth's crust, atmospheric disturbances can take place. In accordance with Shalimov and Gokhberg (1998), bay-formed pulses of gravity waves in the atmosphere with characteristic time scales of 2–3 h, occurring in the near-surface atmospheric layers and propagating into the ionosphere, could cause modifications of the parameters of the ionosphere with the same time scales.

However, a peculiarity of the gravity waves is their almost horizontal propagation (Brunelli and Namgaladze, 1988; Francis, 1975). According to the dispersion equation, the distance from the region of the generation of the waves (with periods of about 2 h) to the observational point is estimated at about 1500 km. Remark that along such a distance the damping of the waves may be essential. Thus, the ionospheric effects should occur at sufficiently long distances from the epicenters and they may not appear above the epicenters.

Correspondingly, the increase of the number of bay-formed disturbances with time scales of 2–3 h in the ionosphere at altitudes of the order of 300 km and at distances less than 500 km from the epicenter cannot be explained by the propagation of acoustic-gravity waves from the zones of earthquake preparation.

Thus, a probable mechanism exists according to which not an acoustic-gravity disturbance with duration 2–3 h cause effects in the ionosphere, but a series of acoustic pulses (with time scales of minutes) lasting for 2–3 h act on the lower ionosphere. These acoustical disturbances can propagate nearly vertically and, due to the ions–neutrals collisions, they can lead ionospheric disturbances. This mechanism is mentioned in Liperovsky et al. (2000).

An alternative mechanism which could justify the observed effects is as follows. Some increase in the concentration of radon and other radioactive gases generally take place in the region of earthquakes preparation (Gokhberg et al., 1996). So, it is possible to suppose that the increasing of radioactivity happens by short impulses of a total duration up to 2–3 h being the relaxation due to winds and other meteorological factors and diffusion in atmosphere. Then an increasing of the atmosphere conductivity correspondingly happens and it leads to an increasing of the quasi stationary electrostatic field of the ionosphere. Thus, above the region of earthquake preparation, impulses of electrostatic fields appear with total duration of series up to 2–3 h. These fields lead to the vertical local movement of ionospheric plasma with the same character time, 2–3 h. On the fixed high of 300 km the vertical gradient of plasma density is sufficient enough, and increasing or decreasing of plasma density (f300) are observed by vertical sounding on fixed height which is lower than maximal electron density. Processes vertical movements of plasma in the region of F2 maximum practically do not cause the change of maximal density (and the frequency foF2), but only the height of the maximal plasma density could change.

So, we have a possible qualitative explanation why the number of 2–3 h variations of electron density is not increased on the height of F2 maximum, whereas it increased at fixed lower height of 300 km and in the E-region. The small decreasing of 2–3 h variations in foF2 could be explained by a total ionosphere heating and an activation of diffusion processes before earthquakes.

4. Conclusion

The study we presented indicates that before earthquakes with $M > 4.5$ and distances $R < 500$ km the number of 2–3 h bay-formed variations in the lower F-layer of the ionosphere (virtual altitudes of 300 km) increases while the number of the same disturbances in the upper ionospheric F-layer does not change before earthquakes with $M \leqslant 5.5$ and slightly decreases (at 9%) before stronger earthquakes $M \geqslant 5.6$. These effects confirm the possible existence of a seismo-ionospheric coupling during the preparatory phase of an earthquake.

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