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Abstract. In the present work, phenomena in the ionosphere are studied, which are connected with earthquakes (16 events) having a depth of less than 50 km and a magnitude M larger than 4. Analysed are night-time Es-spread effects using data of the vertical sounding station Petropavlovsk-Kamchatsky ($\varphi = 53.0^\circ$, $\lambda = 158.7^\circ$) from May 2004 until August 2004 registered every 15 minutes. It is found that the maximum distance of the earthquake from the sounding station, where pre-seismic phenomena are yet observable, depends on the magnitude of the earthquake. Further it is shown that 1-2 days before the earthquakes, in the pre-midnight hours, the appearance of Es-spread increases. The reliability of this increase amounts to 0.95.

2 Method of analysis

In the present work earthquakes with magnitudes of $M > 4.0$ and depths of up to 50 km are studied. The investigation of such rather weak earthquakes is reasonable as the sporadic E-layers have only a distance of about $h \approx 100$ km from the surface of the earth, and the seismo-ionospheric effects are apparently stronger than in the case of the F-layer situated at an altitude of about 300 km.

The occurrence frequency of Es-spread on ionograms is analyzed, which reflects the degree of turbulization of the plasma of sporadic layers. The authors make the assumption that turbulence in the sporadic Es-layers may be caused by acoustic waves with periods of 20 s to 5 min. Further, the radius of the earthquake preparation region may be estimated using the Dobrovolsky formula, $R \sim \exp(M)$, where M describes the magnitude of the earthquake. According to geometric considerations, weak disturbances propagating upwards from the surface of the earth can modify the ionosphere, if the dimension of the earthquake preparation region is of the order of the distance between the surface of the earth and the E-region, that means if $h \sim d = 2R$. Consequently, the magnitudes of the earthquakes causing an Es-layer turbulization should be larger than 4. Besides, the maximum amplitude of an acoustic disturbance propagating up into the atmosphere occurs for vertically moving disturbances. Consequently, the authors propose to study earthquakes with preparation regions which are not situated too far from the vertical sounding station. Thus, only earthquakes with distances from the sounding station of $\Delta L = L - R < 100$ km are taken into account. From May 2004 until August 2004, only 25 such earthquakes happened. Some of the events occurred on the same day, therefore, in total, 16 days with earthquakes were analysed. The according Es-spread data were all registered by the ionospheric vertical sounding station Paratunka ($\varphi = 53.0^\circ$, $\lambda = 158.7^\circ$, near Petropavlovsk-Kamchatsky) in the time interval May-August 2004 at night (20 LT - 5 LT) every 15 minutes (37 measurements were made during one

1 Introduction

Recently, in connection with earthquake preparation processes, in a series of works the Es-spread phenomenon is studied (Silina et al. 2001, Liperovsky et al. 2005). Es-spread occurs as diffusivity, that means as smearing of the traces of sporadic Es-layers on ionograms of vertical sounding stations, reflecting the turbulization of the sporadic layers (Bowman 1985, Whitehead 1989). Es-spread is mainly observed at night, and its observation probability depends on the season and on the solar activity.

In a series of former works, it was found that Es-spread observation increases 1-3 days before an earthquake. The Es-spread decrease was analysed for earthquakes with different magnitudes larger than 4 and at different distances from the sounding station up to 600 km. All these former works took into account earthquakes of Central Asia (Liperovsky et al. 2000, 2005, Silina et al. 2001). In the present work ionospheric effects of earthquakes with epicenters below sea are investigated and pre-seismic effects are analyzed as a function of the local time.

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night).

Earthquakes which happened May-August 2004 and are taken into account in the present work:

month	day	lat. N	long. E	h	M	R	ΔL
5	18	52.9	169.1	39	5.0	130	-20
5	23	51.7	159.0	48	4.7	160	+40
5	28	51.4	159.9	40	4.7	210	+100
6	12	53.3	160.4	42	4.2	150	+80
6	13	53.7	160.8	34	4.8	180	+60
6	18	53.1	160.3	38	4.2	140	+70
6	27	52.2	160.4	35	5.0	170	+20
7	3	53.0	160.7	32	4.5	160	+70
7	16	40.0	156.6	18	5.6	370	+100
7	26	53.6	160.8	40	4.9	180	+40
8	4	52.1	159.9	8	5.8	140	-190
8	5	52.3	159.9	0	4.2	140	+70
8	6	52.1	160.0	25	4.3	150	+80
8	14	53.3	160.6	33	4.2	160	+90
8	16	53.3	160.6	40	4.4	160	+80
8	30	49.4	157.4	40	6.0	400	0

In the works by Liperovsky et al. (2000, 2005) and Silina et al. (2001), it is shown that 1-3 days before an earthquake the probability of the observation of diffusivity of the Es-layer, that means of Es-spread, increases. Thus, in the present work the days -2, -1, and 0 before an earthquake are taken to be the “seismoactive” ones. The remaining days are considered to be “background” ones. Further, for all 37 experiments, the number of Es-spread observations is found separately for the “seismoactive” and “background” times. Such an approach makes it possible to find out the day time at which Es-spread caused by earthquake preparation processes is observable.

3 Observational results

In case of the studied earthquakes, the average occurrence probability of Es-spread during “seismoactive nights” amounts to 0.24, and on background days it equals 0.16. Investigating the time of the Es-spread occurrence, for every hour of the day, the total number of observed Es-spread effects is determined. As result it is found that at seismo-active days, a distinct maximum of the number of Es-spread phenomena appears two hours before midnight. In Fig. 1, the number of Es-spread observations is presented as function of the local time for “background” and “seismoactive” days separately.

The seismo-active time interval of the two hours before midnight is in agreement with the results of the observation of ULF-fields connected with earthquakes (Molchanov et al. 2004, 2005). By Molchanov et al. (2004, 2005) ULF variations of the magnetic field are found in the frequency region of 0.05-0.2 Hz. The authors of the present work suggest that the increase of the Es-spread phenomena before earthquakes

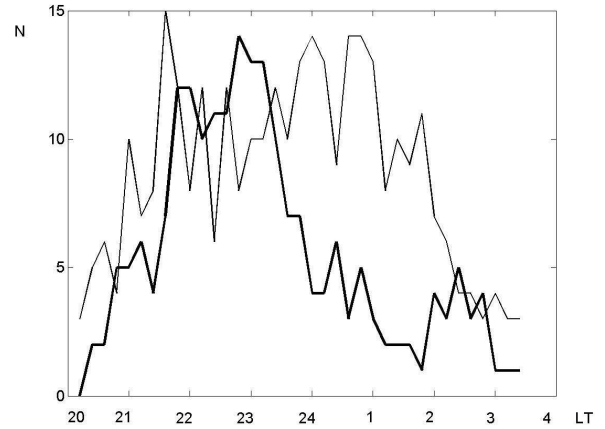


Fig. 1. Number of Es-spread observations as function of the local time LT for “background” days (thin line) and “seismoactive” (-2,-1,0) days (thick line).

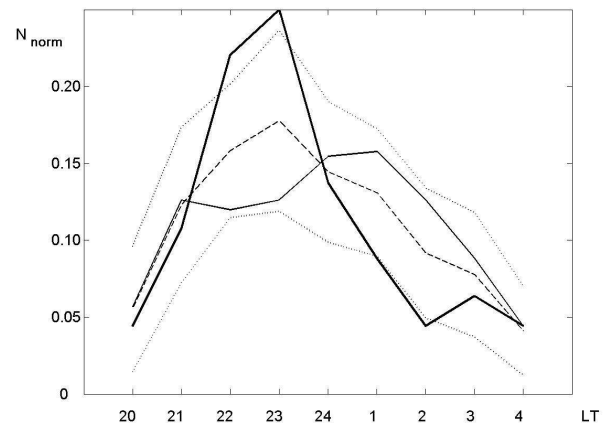


Fig. 2. Normalized number of Es-spread observations as function of local time LT. The solid thick line shows “seismoactive” days, the dashed line describes model results for virtual earthquakes, the dotted lines gives the interval $\pm 2\sigma$, and the solid thin line presents “background” days.

is caused by an enhanced activity of acoustic pulses with frequencies of the order of 0.05 Hz, which propagate from the region of earthquake preparation up into the atmosphere and ionosphere. It might be possible that both the acoustic pulses and the ULF variations are caused by the same reason. It should be underlined that an increase of the number of Es-spread effects was not found for the earthquakes appearing during the time of solar activity maximum 1988-1989 (Liper-

ovsky et al. 2005). Thus one may conclude that the dissipation of the acoustic pulses at solar activity maximum increases so strongly, that before the earthquakes a remarkable modification of the turbulization of the sporadic Es-layer is not possible. Thus, the reliability of the here obtained increase of the Es-spread phenomena before earthquakes has to be estimated.

To neglect high-frequency noise, the number of Es-spread observations is found for every hour (using 4 consecutive ionogrammes obtained every 15 minutes, that means together within one hour) for the (-2,-1,0) days and the “background” days separately. Further, the obtained nine values are normalized by their sum. As result the numbers N_{norm} are found, which are presented in Fig. 2 as function of the local time.

To prove the statistical reliability of the obtained increase of the Es-spread phenomena the method of modelling of random processes is applied. Therefore, 200 series consisting every of 16 virtual earthquakes are constructed. Then for every series the normalized number of Es-spread observations is found for the days (-2, -1, 0). Besides, for all the 200 series the mean values of the numbers of observations and the intervals of reliability $\pm 2\sigma$ are calculated (see Fig. 2). There are obtained values for the real earthquakes which are beyond the interval of reliability which means that the reliability of the obtained increase of the Es-spread phenomena is better than 0.95.

To estimate the stability of the phenomenon, the interval of reliability 2σ is also calculated for the real earthquakes (Fig. 3). To do so, from the 16 analysed earthquakes 2/3 are taken randomly (i.e. 10 events). This procedure is done 200 times, and for every of the 200 sets of 10 earthquakes the normalized number of observations of Es-spread during the days (-2,-1,0) is determined. Further, for the 200 sets of normalized values, the mean values and the interval of reliability are calculated. The interval of reliability of the real earthquakes is smaller that the interval of reliability of the virtual events by a factor of $\sqrt{3/2}$. In Figure 3, it can be seen that the curve of the mean value of the normalized number of Es-spread observations for the 200 series of 10 earthquakes and the curve for the real 16 earthquakes are situated rather narrow. That means, the obtained phenomenon is stable.

4 Conclusions

Analysing Es-spread phenomena of the ionograms of the vertical sounding station Paratunka (Kamchatka) it is shown that 1-2 days before earthquakes, even before rather weak ones, the turbulization of the plasma of sporadic Es-layers increases. Thus the number of Es-spread phenomena increases. The maximum growth of the number of Es-spread phenomena before earthquakes is obtained two hours before midnight. The authors assume that pre-seismic Es-spread takes place if the magnitude M of the earthquake and the distance between the epicenter and the vertical sounding station L are connected by the relation $L - \exp(M) < 100$ km. Further

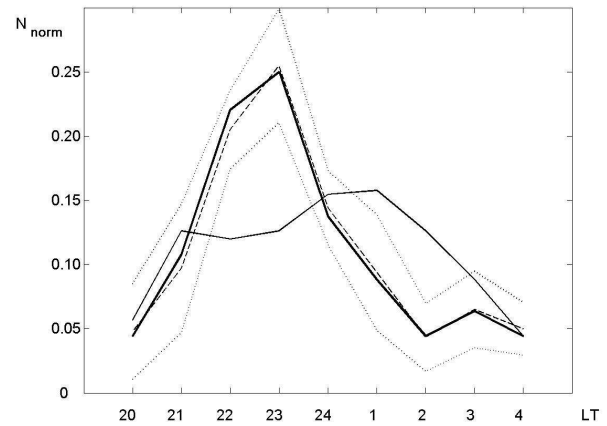


Fig. 3. Normalized number of Es-spread observations as function of the local time LT. The solid thick line shows “seismoactive” days, the dashed line describes model results for the sets of two third of the earthquakes, the dotted lines gives the interval $\pm 2\sigma$, and the solid thin line presents “background” days.

they suggest that pre-seismic Es-spread is caused by an enhanced activity of acoustic pulses with frequencies less than 0.05 Hz (i.e. with periods of more than 20 sec and up to a few minutes), which propagate from the region of earthquake preparation up into the atmosphere and ionosphere.

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