Daytime variations of foE connected to earthquakes

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Abstract. In the present work it is shown that, in accordance with the observations of the vertical sounding station “Tashkent”, the critical foE-frequency of the daytime E-layer increases about one day before winter-earthquakes with magnitudes M > 5 and depths of the epicentre of h < 60 km, which appeared at distances of R < 2000 km from the station. The reliability of the result is larger than 99 %. The phenomenon is not observed for summer-earthquakes. It seems to be determined by the atmospheric wind system. Further, the variations of the foE-frequency are compared with possible simultaneous variations of the critical frequency foF2 of the F2-layer. First results show that only very large changes of the ionisation density in the E-layer influence the ionisation density in the F-region. Therefore, no synchronous growth of the foE- and foF2-frequencies 1–2 days before seismic shocks could be observed.

1 Introduction

The E-region of the ionosphere is situated at h ≈ 90–140 km above the Earth’s surface. Its ionisation density amounts to N ≈ 10⁵ cm⁻³ at daytime, and decreases by about 3–4 orders of magnitude at night (Antonova et al., 1996). The mid-latitudinal daytime E-layer is mainly formed by the ionisation of neutral O₂-molecules by two close EUV lines with wavelengths of 977 A (CIII) and 1025.7 A (HLyβ), providing 80–90 % of the total ionisation rate (Mikhailov et al., 2007). The remainder of the ions is provided by the x-ray radiation with wavelengths below 100 A (Ivanov-Kholodny et al., 1996). The critical frequency foE of the daytime E-layer is generally described by a classical theory already introduced by Chapman in the 1930s (Chapman, 1931). The frequency, above all, depends on the position of the Sun above the horizon, and of course on the solar activity. Additionally, it is modified by the concentration of the O₂-molecules and its altitudinal scale, as well as by the ionisation and absorption cross sections of the material (Mikhailov et al., 2007). Thus, the behavior of foE is, above all, determined by the daily and seasonal changes of the solar activity, and also by the 11-yr and 27-days solar cycles. Additionally, the frequency is weakly influenced by disturbances of the geomagnetic field, by electrical disturbances propagating from the F-layer downwards, as well as by variations of the electric field and perturbations of acoustic nature propagating upwards from the neutral atmosphere. The influence of meteorological effects on the E-layer, and particularly on the foE-frequency, was studied by Danilov (1989). One may expect that electrical, acoustic, and acoustico-gravity disturbances occurring in the lower atmosphere during earthquake preparation times influence the variations of the foE-frequency. But as the foE-frequency, compared with other characteristic frequencies of the ionosphere, is rather stable with respect to external influences, and as its changes caused by disturbances of non-solar nature amount only to about one percent, it was considered to be only weakly sensitive to earthquake preparation processes. Therefore, the foE-frequency was only seldom analysed searching for seismo-ionospheric effects. Only in the work by Ivan-Kholodnyi and Tchertoprud (1998), an increase of foE about two days before some (≈ 20) strong earthquakes was mentioned. On the other side, in some works (Liperovskaya et al., 2006, 2008, 2009) it was already concluded that 3–5 days before strong earthquakes the critical frequency foF2 of the F2-layer is somewhat modified.

The aim of the present work is the statistical proof of seismo-ionospheric effects in the foE-variations, attempting to define under which conditions the characteristic foE-frequency increases 1–2 days before earthquakes. Further, a first comparison of the variations of the foE-frequency with
simultaneous variations of the critical frequency foF2 of the F2-layer before earthquakes is presented.

2 Method of analysis

In the present work, effects of earthquakes on the E-layer and F-layer of the ionosphere before seismic shocks are investigated. Therein, earthquakes with magnitudes $M > 5$, epicentres situated at a distance from the vertical sounding station smaller than $R = 2000$ km, and a depth of the source $h < 60$ km are taken into account. Data from the “Tashkent” station in Middle Asia (latitude $\varphi = 41.3^\circ$ N, longitude $\lambda = 69.6^\circ$ E), which are published online (http://spidr.ngdc.noaa.gov/spidr/), are used.

For the study of seismo-ionospheric phenomena in the E-layer of the ionosphere, variations of the critical daytime foE-frequency are considered. The hours from 11:00 LT to 17:00 LT are taken as daytime, as the time when the degree of ionisation of the ionosphere is at maximum and the dependence of the degree of ionisation on the time is not so strong as in the other hours. For the analysis, the data averaged over the introduced interval of 11:00–17:00 LT, foEday are used. foEday is found when at least four values of the averages over the six daytime hours exist.

To exclude the seasonal dependence of the foEday-values, the values of foE11days, calculated using linear interpolation over 11 days (from day ($-5$) until day $(+5)$), were subtracted from the values of foEday: $\Delta E(i) = f_oE_{\text{day}}(i) - f_oE_{11\text{days}}(i)$. The short time interval of 11 days is selected to also decrease the influence of the 27-days solar cycle. It is not possible to exclude the seasonal dependence completely. But, as will be shown below, the seasonal dependence remaining after the described averaging procedure is much smaller than the change of $\Delta E(i)$ by the ionospheric earthquake preparation processes.

From the obtained $\Delta E(i)$-values, all variations which have an absolute value larger than 2 MHz are then excluded. The number of such values is about 1 % of the total data (84 days of a total of 6425 days). The main part of the excluded data is related to strong geomagnetic and solar disturbances. Spikes in the $\Delta E(i)$-values also occur, the reason for which is unknown. It is reasonable to also omit these data before one calculates the mean square deviation $\text{std}(\Delta E(i))$ for 11 days. Further, the $\Delta E(i)$-values are normalized by the mean square deviation $\text{std}(\Delta E(i))$. As a result, every analysed day is characterized by a normalized function $f_oE_{\text{norm}}(i) = \frac{\Delta E(i)}{\text{std}(\Delta E(i))}$.

The ionospheric effects before earthquakes are searched for in front of the background of solar and geomagnetic disturbances. Thus, only such days are considered in which the solar and geomagnetic disturbances are not too large. An accepted opinion about what is “too large” does not exist. In the present work, days with a Wolf number $W > 150$ are neglected. As ionospheric changes may continue some days after strong disturbances, days with a $\Sigma K_p$-index larger than 30 are also not taken into account.

Finally, having performed the data evaluation as described above, excluding days with strong solar and geomagnetic disturbances as previously described was inserted for clarity, the superposition of epoches method (Ambroz, 1979) is applied to earthquakes with magnitudes $M > 5$, distances from the station $R < 2000$ km, and focal depths $h < 60$ km.

3 Seismo-ionospheric effects in the E-layer

Results of the analysis of the foE-data are shown in Fig. 1. The decrease of the mean foEnorm-value three days before the (260 studied) earthquakes (day $(−3)$) and the increase of the value one day before the seismic shocks (day $(−1)$) are demonstrated in Fig. 1. The decrease on day $(−3)$ seems to be random. First, it is unnatural to suggest that a seismo-ionospheric effect is so strongly localized in time a few days before an earthquake. Second, the effect is unstable: studying the dependence of the decrease of foEnorm on the different years, the casual character of the decrease can be seen.

Next, the seasonal dependence of foEnorm on day $(−1)$ before the seismic shock is considered. Figure 2 shows that the increase of foEnorm one day before a seismic shock is observed only in winter. In contrast, no effect is found during the summer months.

Thus, only earthquakes occurring in winter (from October till April, in the months 1, 2, 3, 4, 10, 11, 12) are studied here.
The increase of $\text{foE}_{\text{norm}}$ on the day ($-1$) before winter-earthquakes with magnitudes $M > 5$, distances $R < 2000$ km, and depths $h < 60$ km is considerable. It is larger than $3 \text{ std}$ for a superposition interval of 20 days (see Fig. 3). At a superposition time of 100 days (from day $-50$ till day $+50$), one even finds an increase larger than $4 \text{ std}$. This effect is rather stable, meaning it does not depend on the different years. Figure 4 shows the behaviour of $\text{foE}_{\text{norm}}$ in the years from 1964 till 1988. From these results one may conclude that the increase of $\text{foE}_{\text{norm}}$ on the day ($-1$) is observed for the whole considered time interval. In total, there are analyzed data of 119 earthquakes for the day ($-1$). Dividing the 119 earthquakes into three groups according to growing time, one finds for the first 40 events a mean value of 0.27, for the group 2 of 40 earthquakes a mean value of 0.51, and for the third group of 39 earthquakes a mean value 0.32.

Further, the dependence of $\text{foE}_{\text{norm}}$ of the day ($-1$) on the distance between the earthquake epicentre and the sounding station is studied (Fig. 5). From Fig. 5 one can see a tendency that the maximum increase of $\text{foE}_{\text{norm}}$ occurs at distances of 800–1600 km from the epicentre.

Considering the dependence of the seismo-ionospheric effect on the location of the epicentre for winter-earthquakes, it is found that $\text{foE}_{\text{norm}}$ on the day ($-1$) is anisotropic (Fig. 6). In the case of earthquakes to the west of Tashkent, on day ($-1$), one finds an increase of $\text{foE}_{\text{norm}}$ for 44 seismic shocks and a decrease for 26 shocks. But for seismic events east of Tashkent, an increase on day ($-1$) is observed in 28 cases, and a decrease occurs in 22 events. Earthquakes with an epicentre east of the sounding station mainly contribute to the increase of $\text{foE}_{\text{norm}}$. 

Fig. 2. Seasonal dependence of $\text{foE}_{\text{norm}}$ one day before an earthquake shown by its monthly average values. The dash-dotted line presents the mean value for all days ($-1$) of all data considered.

Fig. 3. Result of the superposition of epoches for $\text{foE}_{\text{norm}}$-values for winter-earthquakes with $M > 5$, $R < 2000$ km, and $h < 60$ km. The superposition time equals 20 days. The red arrow shows the day zero of the earthquakes. The mean value of $\text{foE}_{\text{norm}}(i)$ for the day $i$ during seismo-active times is presented by the solid blue line. The dash-dotted line designates the mean value of $\text{foE}_{\text{norm}}$ for all data considered. The dotted lines show the 95 %-levels (2 std.) and 99 %-levels (3 std.) of reliability obtained using the method of modeling random processes.

Fig. 4. Variations of $\text{foE}_{\text{norm}}$ on the day ($-1$) of all winter-earthquakes in dependence on the year. Every earthquake is presented by a triangle. It is to be seen, that in all the years the number of earthquakes with $\text{foE}_{\text{norm}}$ larger than the mean value is larger than the number of seismic shocks with $\text{foE}_{\text{norm}}$ smaller than the average.
that positive and negative variations of the foF2-frequency at geomagnetic quiet times in the F2-region are mainly due to the atomic oxygen density variations which are presumably the result of the vertical gas motion in the thermosphere, also including E-region heights. Mikhailov et al. (2007) did not find point-to-point correlations between the electron densities in the E- and F2-layer, but only a statistical correlation.

Investigating the critical frequency foF2, data obtained for the same earthquakes with magnitudes \( M > 5 \) and depths of the epicentres \( h < 60 \) km which occurred at a distance \( R < 2000 \) km from the vertical sounding station “Tashkent” are considered. For the study, a method analogous to the method of analysis of the foE-frequency (described in Sect. 2) is applied. The seasonal dependence is excluded and the function foF2norm is constructed, which is normalized by the mean-square deviation. Again, the days with high solar activity and magnetic disturbances are excluded from the analysis. For foF2norm, the superposition of epochs method is also performed. First results of the analysis, obtained for all data (all seasons) are shown in Fig. 7. There, data for foF2 for the same daytime hours of the day \((-1)\) were available for 215 earthquakes. In the case of day \((-1)\), the average value of foF2norm increases and almost reaches the 95% level of reliability. Thus, one might suggest that the increase of the foF2-frequency is connected with the increase of the foE-frequency. Consequently, one might conclude that disturbances of the ionisation density are brought forward by the magnetic field. On the other side, the authors are inclined to assume that the variations obtained on the day \((-1)\) are random. In the case of winter-earthquakes, the increase of the foF2norm-value is rather small (see Fig. 7).

The correlation coefficient of the correlations between foE norm and foF2 norm , calculated taking the complete data into account, is generally low. Thereby, days with high geomagnetic activity mainly contribute to the growth of the coefficient. When investigating seismo-ionospheric effects, days with increased geomagnetic and solar activity are excluded from the analysis and a correlation coefficient of the quiet days (\( \Sigma K_p < 30, W < 100 \)) of 7 per cent is found. If one chooses from all the quiet days only those with very strong (positive or negative) foE norm-values, one obtains a weak increase of the correlation coefficient with growing
foE\textsubscript{norm} (see Table 1). Thus, one may conclude that only very large changes of the ionisation density in the E-layer influence the ionisation density in the F-region. However, such large ionisation densities in the E-layer, and correlated extreme values of foE\textsubscript{norm} at the day (−1), are a very rare phenomenon. Consequently, no synchronous growth of foE\textsubscript{norm} and foF\textsubscript{2}\textsubscript{norm} could be observed.

5 Discussion of the results and conclusions

In the present work it is shown that in accordance to the observations of the vertical sounding station “Tashkent”, the foE-frequency increases about one day before winter-earthquakes with magnitudes \( M > 5 \), \( R < 2000 \) km, and \( h < 60 \) km. The superposition time equals 30 days. The red arrow shows the day zero of the earthquakes. The mean value of foE\textsubscript{norm}(i) for the day \( i \) during seismo-active times is presented by the solid blue line. The dash-dotted line designates the mean value of foF\textsubscript{2}\textsubscript{norm} for all data considered. The dotted lines show the 95 %-levels (2 std.) of reliability obtained using the method of modeling random processes.

![Fig. 7.](image)

Concerning the recombination of ions in the E-layer, it has yet to be mentioned that in this layer in daytime the main ions are NO\textsuperscript{+} and O\textsubscript{2}\textsuperscript{+} ones. Besides, at E-layer altitudes the N\textsubscript{2}\textsuperscript{+}-ions exist. But these ions have a short lifetime, and the O\textsuperscript{+} and N\textsuperscript{+}-ions possess a low recombination coefficient. According to (Danilov, 1989), the effective recombination coefficient is approximately the sum of the recombination coefficients of NO\textsuperscript{+} and O\textsubscript{2}\textsuperscript{+}, which are both proportional to the inverse electron temperature. So, in daytime during the increase of the temperature, the effective recombination coefficient decreases, and the degree of ionisation grows. Thus, also at growing temperature due to the dissipation of acoustic waves, the electron density and therefore also the critical frequency foE grow.

Concerning the foE-variations and possible correlated changes of the critical foF2-frequency before earthquakes, a first analysis showed only small correlations. Electron density changes in the F-layer might be preferably caused by acoustic and electric disturbances propagating, contrary to acoustic-gravity waves, mainly vertically upwards. But this is a topic of future research work.

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