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BRIEF COMMUNICATIONS

Local-Time Dependence of Seismo-Ionospheric Variations at the *F*-Layer Maximum

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Abstract—Variations in the critical frequencies of the ionospheric *F*-layer in seismoactive regions are studied for several days before and after strong ($M > 5$) earthquakes out of a series ($n > 50$) of earthquakes epicenters distributed over the Earth. Although the departures of the critical frequency from the average value vary widely, a regularity is found in the occurrence of positive and negative departures, which has the form of a steady local-time dependence. A discussion is presented for the possible relationship of the observed variations with the daily variations of plasmaspheric fluxes of oxygen atomic ions and seismogenic electric fields in the ionosphere.

INTRODUCTION

Ionospheric effects caused by the processes in the Earth's crust which are related to the preparation of strong earthquakes have been discussed over several years [1, 2]. Before strong earthquakes ($M > 5$), a modification of the ionospheric plasma takes place, as established experimentally by remote-sounding methods (ground-based and topside vertical sounding) [3–7] and in situ measurements by satellite probes [8]. Out of a number of space-plasma parameters, whose seismic-related variations were revealed experimentally, the electron density N_mF2 at the ionospheric *F*-layer maximum is among the most sensitive ones. It can be measured by the vertical-sounding method either by a ground-based ionosonde network or from satellites.

For this parameter, the largest amount of experimental data have been collected, which relate to ionospheric variations during strong earthquakes, from the 1960s to the present time. This makes it possible to study regularities in the ionospheric electron-density variations during such periods.

The investigators of seismo-ionospheric variations report observations of both positive [4–6] and negative [3, 7] variations in the electron density. Up to now, however, no regularity in sign changes has been found for seismo-ionospheric variations. Our analysis of experimental data makes it possible to reveal the local-time dependence of seismo-ionospheric variations. The results of this analysis are presented here.

EXPERIMENTAL DATA ANALYSIS

Figure 1 shows examples of seismo-ionospheric variations for a number of typical cases, as inferred from ground-based vertical sounding at stations situated near earthquake epicenters. As seen from the figure, only negative seismo-ionospheric disturbances are observed for some earthquakes, only positive for some others, and disturbances of both signs for the remaining ones. As a result of our analysis, the following specific features were distinguished in critical frequency variations recorded during the preparation of strong earthquakes:

(1) The durations of seismo-ionospheric variations are shorter (3–4 h) than those of magnetic-storm variations (8–36 h);

(2) Seismo-ionospheric variations appear during several (2–3) days before an earthquake, at the same local time;

(3) The sign of seismo-ionospheric variations is strictly determined by the local time (for example, only negative variations are observed at 3–4 LT; only positive variations, at 12–14 UT).

We analyzed 56 strong earthquakes for which records were available from vertical-sounding stations located within the earthquake preparation zone. All data were reduced by the same technique. For each nine-day period (seven days before the main shock and two days after), the mean daily variations of the critical frequency were calculated and, then, the deviation $\overline{f_0F2}$ from the mean value was determined. For the analysis, only magnetically quiet periods were selected ($K_p < 3$). In some cases, a magnetic storm was observed on the next day after the earthquake. The maximum deviation δf_0F2 from the average (precursor), in percent, was represented in the plot shown in Fig. 2, as a function of local time. As a result, a synthesized plot was obtained which summarizes data for many earthquakes which occurred in various regions of the Earth. Nevertheless, this method of data reduction allowed revealing the local-time dependence of seismo-ionospheric variations, which manifests itself in periodic changes of the sigh of anomalous variations.

Before making assumptions on to the nature of the observed variations, it is necessary to assess how their character changes with altitude. As was reported in [3, 9], modifications of the electron-density height profile occur not only near the F-layer maximum, but also in a fairly wide altitude range within both the inner and the outer ionosphere. The question arises as to whether the electron density is redistributed over heights with the total electron content (TEC) in the entire ionosphere remaining unchanged or the TEC changes as well. TEC variations over seismo-active regions were studied, with the inclusion of periods of several days before strong earthquakes, from the *TOPEX/POSEIDON* measurements [10] along its trajectory. No efforts to obtain the local-time dependence of the observed seismo-ionospheric variations were made in [10]; however, it can be concluded from the data presented that the morphology of the observed variations completely coincides with the observed variations of the critical frequency:

(1) Both negative and positive variations of the TEC are observed over seismo-active regions;

(2) The time advance of the observed variations relative to the main shock coincides with the respective parameter for the critical frequency;

(3) The sign of the variation for a given moment of local time coincides with the variation sign implied by the dependence of the critical frequencies (Fig. 2).

DISCUSSION OF THE RESULTS

Thus, we can conclude that in both experimental series, the same effect is observed, related to the filling and devastation of the geomagnetic field lines anchored in the earthquake preparation region. The periodic (with a period of ~6 hours) character of the observed variations indicates their relation to the diurnal variations of plasmaspheric fluxes of ions of ionospheric origin, in particular, O^+ oxygen ions. Figure 3 shows the daily variations of the plasmaspheric O^+ fluxes calculated for three different latitudes of the northern hemisphere and a longitude of 20° E according to the FLIP model [11]. As seen from the figure, the periodicity of the plasmaspheric fluxes of atomic-oxygen ions is precisely the same as that of the local-time seismo-ionospheric variations of the critical frequency, presented in Fig. 2. During the periods when the fluxes are directed from the ionosphere to the magnetosphere, the seismo-ionospheric variations are negative, whereas during the periods of downward fluxes, these variations are positive. It should be stressed that Fig. 2 presents the deviations from the daily average critical frequency for the nine-day period of observations. Thus, seismo-ionospheric variations manifest themselves in the form of the amplification of the natural daily variations of the atomic-oxygen ion content. These variations can be represented as an additional ion flux coinciding in sign with the direction of the normally observed plasmaspheric flux of these ions. Such additional fluxes may

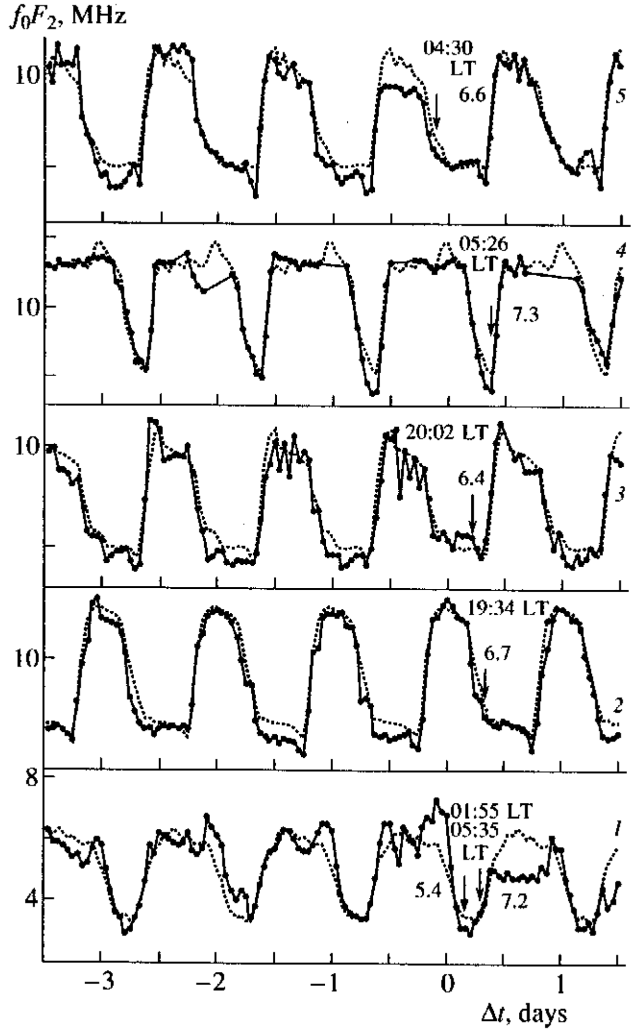

Fig. 1. Examples of comparison between daily f_0F2 variations (dots) and their monthly median values (dashes) for three days before and one day after an eathquake according to the data of ground-based vertical-sounding stations for different earthquakes: (*1*) Mil'kovo (Sept. 5, 1971, 18:35 UT, $M = 7.2$ [4]); (*2*) Rome (Nov. 23, 1980, 18:34 UT, $M = 6.7$ [7]); (*3*) Norfolk, (June 19, 1980, 08:34 UT, $M = 6.4$ [3]); (*4*) Vanimo (July 16, 1980, 05:26 UT, $M = 7.3$ [3]); (*5*) Norfolk, (July 14, 1980, 16:15 UT, $M = 6.6$ [3]). Times of shocks are indicated by arrows.

arise under the action of an electric field of seismogenic origin, which penetrates into the ionosphere over the zone of preparation of a strong earthquake [12].

Up to now, the following question has remained open: why, for each separate ionospheric station (of for each separate earthquake event), a precursor appears in ionospheric variations not at any time of the day, but only in certain definite hours (either morning or afternoon variations). The assumption exists that this effect is related to the moment τ_S of the main shock of the earthquake considered. The process of the development of the earthquake final stage, as well as the processes leading to the generation of seismogenic electric fields, seems to have a fixed duration. In this case, each of the

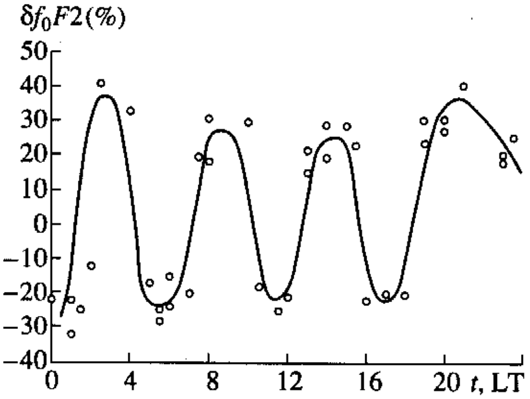

Fig. 2. Dependence of δf_0F2 on local time. Positive values of δf_0F2 correspond to increases and negative, to decreases in the electron density at the maximum of the $F2$-layer compared to the mean value for the time interval considered.

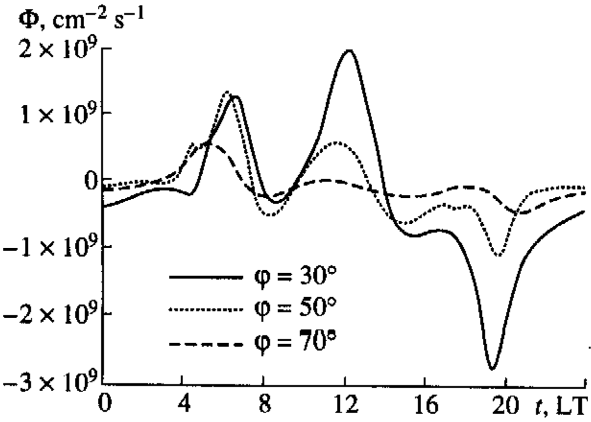

Fig. 3. Daily variations of plasmaspheric fluxes of atomic oxygen ions O^+ for a longitude of 20° E in the northern hemisphere, as calculated from the FLIP model [11].

observed effects will be related to τ_S, with a corresponding time advance t_a. Then the precursor local time will be $\tau_S - t_a$. Another possible reason is related to the meteorological conditions over the earthquake preparation zone. The magnitude of the near-ground electric field of seismogenic origin related to the emanation of radon and fine aerosols from the Earth's crust, substantially depends on the eddy-diffusion coefficient, which may vary during a day. Therefore, ionospheric precursors will be observed during those local-time intervals when the magnitude of the anomalous electric field will be sufficient to produce additional ionospheric effects.

CONCLUSION

We used our analysis of the measurements of the $F2$-layer critical frequency (f_0F2), made by means of ground-based and satellite vertical ionospheric sounding, to investigate anomalous f_0F2 variations (deviations from the nine-day averages of diurnal variations) associated with earthquake preparation. The sign changes of the anomalous variations are found to be local-time-dependent rather than chaotic. An empirical relationship is obtained for the local-time dependence of seismo-ionospheric variations (Fig. 2). A suggestion is also put forward as to the nature of the observed diurnal regularity in the occurrence of positive and negative variations of δf_0F2. In particular, the observed precursor effects in f_0F2 are shown to be correlated with the diurnal variations of the atomic-oxygen ion fluxes in the plasmasphere.

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