Ionospheric variability unrelated to solar and geomagnetic activity

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Abstract

Ionospheric variability has become a subject of one of the most intensive studies in the area of ionospheric physics. Regardless of our improved knowledge of the ionosphere dynamics, the day-to-day variability still lies within the framework of statistical estimations and the underlying physical mechanisms are far from being fully understood. Significant deviations from monthly median values are observed from time to time in ionospheric records during completely quiet solar and geophysical conditions and are not fully understood. Recently the important role of the large scale vertical atmospheric electric fields penetrating into the ionosphere was revealed. The origin of such fields can be different, starting from orographic effect up to seismic activity. The recently published physical model of electric field effect on the ionosphere at least in part explains the ionospheric variability and the present paper is a modest attempt to demonstrate the effects of anomalous electric fields on the ionosphere using some examples.
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1. Introduction

Statistical parameters of the day-to-day ionospheric variability were intensively studied recently (Forbes et al., 2000; Rishbeth and Mendillo, 2001; Bradley and Cander, 2002). Possible sources of that variability are effects from below as proposed by Kazimirovski (2002) and Mendillo et al. (2002). But the main source proposed by these authors was seen in the movements of the neutral atmosphere. The papers are well supported by experimental evidence, but there still remains a component of variability which is not described in these papers. Pulinets et al. (1998a) proposed the atmospheric electric field as one of the sources of day-to-day variability. Among the possible sources of such an anomalous electric field, which is able to modify the ionosphere, that have been considered are orographic effects, severe thunderstorms, radioactive pollution, large sand storms and seismic activity. The physical model explaining the effect of large scale electric fields on the ionosphere is described in Pulinets et al. (2000). The part of the model explaining the electric field penetration into the ionosphere is based on the formulation of Park and Dejnakarintra (1973) which has been checked many times and seems to work (Rodger et al., 1998).

In the present paper, several examples of experimental data were collected that demonstrate the different cases of ionospheric variability connected with the different sources of anomalous electric fields. All of them were collected during quiet solar and geomagnetic conditions, and their morphology indicates their possible connections with the proposed sources.

2. Orographic effect

The mountain streamline effect was observed many times in atmospheric parameters and described in the

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literature, for example, as an effect on the ozone concentration (Kazimirovsky and Matafonov, 1998). The Andes are one of the largest mountain systems in the world occupying practically all of the western part of the South American continent. Their meridional orientation creates many interesting effects in the atmosphere. We will demonstrate that this effect may be observed not only in the atmosphere, but also in the ionosphere. Fig. 1(a) shows a map of the critical frequency distribution obtained by the Intercosmos-19 satellite topside sounder in July 1980 (winter in the southern hemisphere). One can clearly see the quasi-meridional structure in the ionosphere practically along all of South America. This distribution is very unusual because all large scale ionospheric structures are stretched in a longitudinal direction due to the geomagnetic field control of the ionosphere. The longitudinal cross-section along 25°S is shown in Fig. 1(b). Points indicate the critical frequency, and the continuous line the geodetic level of the ground surface. This effect was partly described in Pulinets et al. (1998b) where the electric field source was attributed to activation of the system of tectonic faults. Here, we would like to present another interpretation. In winter time in South America strong wet winds from the west are often observed. They loose their moisture upon encountering the Andes and descend to the plain as a hot (air heat-

ing due to the friction with mountains) dry wind named "zonda" in Argentina (Campetella and Vera, 2002). In these circumstances the strong frictional electric field along the Andes system may be generated which affects the ionosphere.

3. Effect of the thunderstorm electric fields

The effect of thunderstorm cloud electric fields in the ionosphere was calculated by various authors (Park and Dejnakarintra, 1973; Tzur and Roble, 1985; Hegai et al., 1990; Rodger et al., 1998). Regardless of the differences in the quantitative estimates, nobody neglects such a possibility. Here we are speaking about the quasi-static electric field. Other proofs of the direct coupling between the atmosphere and ionosphere were obtained recently after the discovery of red sprites. Theoretical calculations furthermore indicate a possible effect of sprites on the ionosphere (Pasko et al., 2001). Fig. 2 demonstrates the possible result of the thunderstorm electric field effect on the ionosphere. The results were obtained at the Chung-Li ionospheric station during a severe thunderstorm connected with the passing of an atmospheric front which was registered by remote sensing satellites. The radar reflections from the thunderstorm cloud, and lightning detector data are shown in
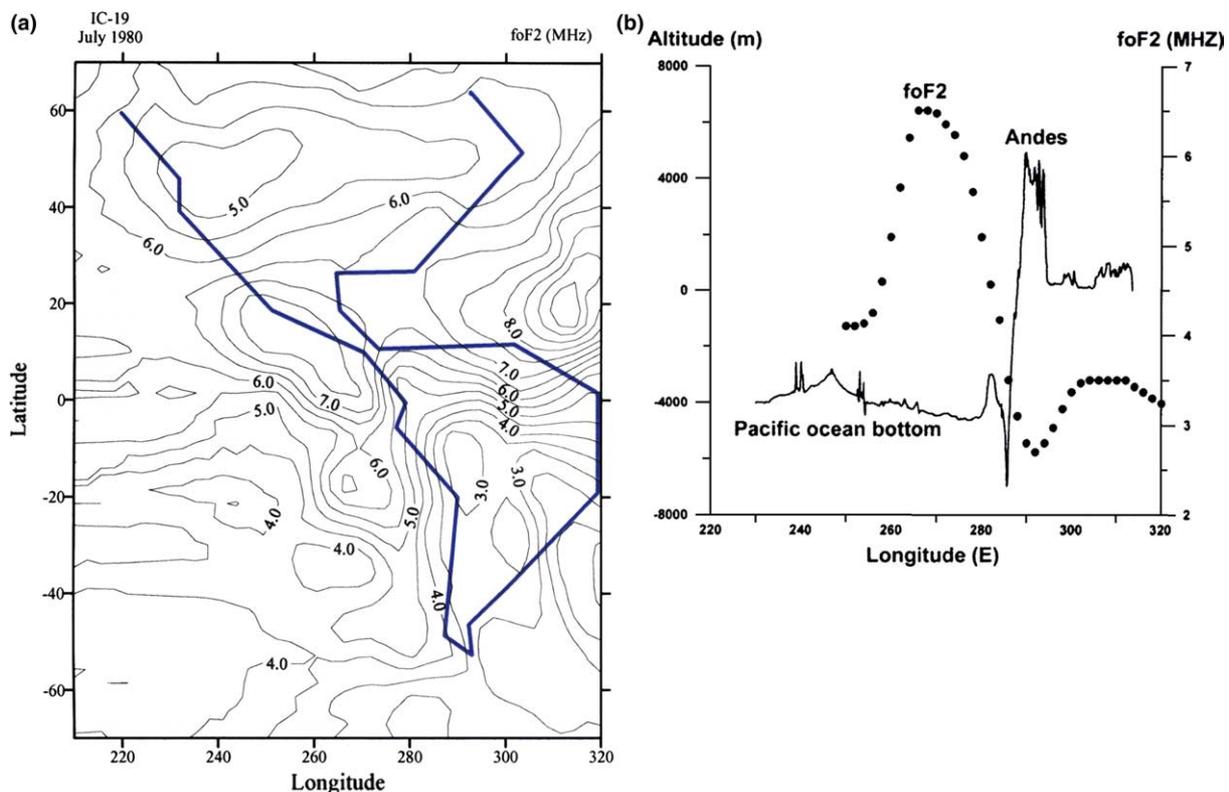

Fig. 1. (a) Map of the critical frequency distribution for 15–16 of July 1980 (05-06 LT) constructed using the Intercosmos-19 satellite topside sounding data. Bold lines indicate the contours of the continents. (b) The critical frequency (points and right vertical axis) variation along 25°S longitude. The continuous line (and left vertical axis) shows the ground geodetic level.
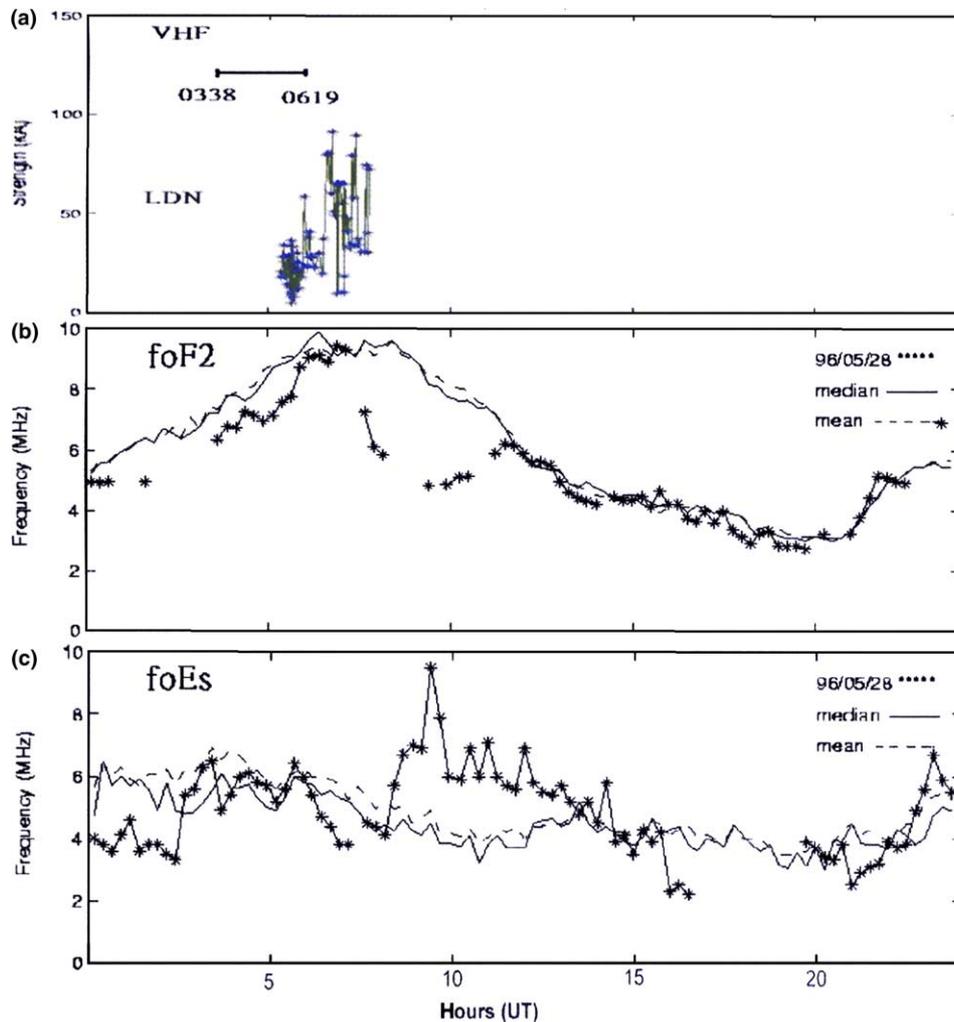
Fig. 2. (a) Thunderstorm cloud registration by VHF radar (horizontal bar) and by lightning detector. (b) critical frequency variations, (*); monthly median, continuous line; monthly mean, dashed line. (c) The same but for f_{o}Es.

Fig. 2(a). Simultaneous variations of the critical frequency $f_{o}F2$ and the sporadic E-layer critical frequency f_{o}Es are shown in the Figs. 2(b) and (c), respectively. Strong depletion of the F2-layer critical frequency, with a simultaneous intensification of the sporadic E-layer, are obvious effects which start at the end of a thunderstorm. This example is one of several recorded cases of ionospheric variations during thunderstorms demonstrating the same morphology.

4. Effect of radioactive pollution

Strong atmospheric electric fields registered during nuclear tests are well known. They are the result of air ionization with the subsequent electric field generation as described by Pulinets et al. (2000). Our modern history has given us the sad opportunity to check these effects after two catastrophes at nuclear plants in the United States (Three- Mile Island incident on 23 of March 1979) and the Soviet Union (Chernobyl catastro-

phe on 26 of April 1986). The case of ionospheric modification after the Three-Mile Island reactor explosion as registered by Intercosmos-19 satellite was published by Pulinets et al. (2000), and to save space we will here only demonstrate the possible effect of the Chernobyl reactor explosion registered by the Kiev ionospheric station (Fig. 3). Atmospheric conditions were not favorable for registration because of the wind blowing in a direction opposite to the ionospheric station, so the observed effect was only weak. The second complication were two strong consecutive magnetic storms starting on 2 of May which makes it only possible to analyze the first few days after the reactor explosion. The results are presented in Fig. 3. Fig. 3(a) demonstrates the gradual growth of the sporadic E activity from the moment of the reactor explosion at 02:24 on 26 of April until the open fire was covered with earth from helicopters. In the F2 layer only very minor changes can be observed (Fig. 3(b)) which are expressed in the character of $\Delta f_{o}F2$ variations after the moment of the reactor explosion until the moment of the magnetic storm commencement indicated by
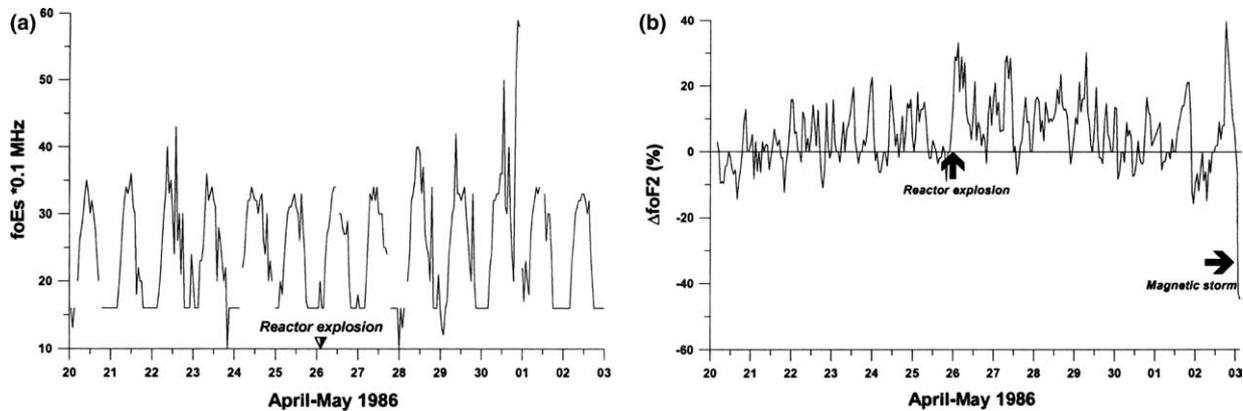
Fig. 3. (a) Variation of the f_oEs around the time of the Chernobyl atomic reactor explosion above the Kiev ionospheric station. (b) Critical frequency deviation Δf_oF2 above the Kiev ionospheric station around the time of the Chernobyl atomic reactor explosion.

the arrows in the figure. The physical mechanism of the electric field generation by the nuclear pollution and the possibility of remote sensing detection were discussed by Boyarchuk et al. (1997a).

5. Ionosphere modification by seismic activity

Up to now the ionospheric variability connected with seismic activity has been the most examined topic of all those mentioned in the present paper. The main phenomenological features of ionospheric variations appearing before strong earthquakes are well established and are described by Pulinets et al. (2003). As concerns the nature of the observed variations, it seems that it is necessary to give a more extended explanation of the seismo-ionospheric coupling physical mechanism due to the novelty of the considered subject. One can find the most recent version of the physical model in (Pulinets and Boyarchuk, 2004). The model can be divided into three parts: anomalous vertical electric field generation in the area of earthquake preparation, electric field penetration into the ionosphere, and electric field effects within the ionosphere and magnetosphere. Its schematic presentation is shown in Fig. 4 and can be briefly described as follows.

The radon emanating from the crust within the seismically active areas (the role of radon as the earthquake precursor is well documented; King, 1996) produces the air ionization. As a result of fast ion-molecular reactions during the interval of $\sim 10^{-7}$ s the main elementary tropospheric ions will be formed: O^-, O_2^-, NO_2^-, NO_3^-, CO_3^- and NO^+, H_3O^+. The large amount of water vapor molecules contained in the troposphere ($\sim 10^{17}$ cm^{-3}), having a noticeable dipole moment $p = 1.87$ D, leads to hydration of elementary ions and formation of ion complexes of a type $NO_2^-(H_2O)_n$ and $NO_3^- \cdot (H_2O)_n$, $NO_3^- \cdot (HNO_3)_n (H_2O)_m$ and $O_2^+(H_2O)_n$, $NO^+(H_2O)_n$, $H^+(H_2O)_m$ and $H_3O^+(H_2O)_n$ which occurs rather fast. The ions $NO_3^-(H_2O)_n$, $NO^-(HNO_3)_n$

$(H_2O)_m$ and $H_3O^+(H_2O)_n$ could be regarded as the main ions of the troposphere. The average lifetime of these ions reaches 30–40 min and more (Smirnov, 1992). The appearance of the heavy charged ion clusters in the troposphere leads to the modification of the vertical electric field which is the part of the global electric circuit providing the electrodynamic coupling between the ground and ionosphere (Roble and Tzur, 1986). A slight modification of the atmospheric electric field in the near ground layer of the troposphere happens everywhere and is named "electrode effect" (Hoppel, 1967; Boyarchuk et al., 1997b). The difference between seismic and non-seismic areas is that the radon emanation in the vicinity of a tectonic fault is higher which produces the higher level of air ionization. Additional sharp increase in the ion content can be provided by gas discharges from the crust (Irwin and Barnes, 1980). These gas discharges raise a large amount of aerosols into the air where they are immediately ionized by radon. The effect of the additional flux of aerosols on the atmospheric electric field is calculated in (Boyarchuk et al., 1998). Another possibility of increased ion concentration is the decay under the gas discharge impact the preliminary prepared quasi neutral complexes composed from positive and negative ion clusters and kept together by weak electrostatic attraction force (Pulinets et al., 2002). Calculations made in the same paper show that the neutral cluster concentration will be of the order of 10^5 cm^{-3}. The decay of neutral clusters under action of the gas discharges lead to sharp increase of the concentration of charged heavy ion clusters within the troposphere and as a result to sharp jumps of the electric field up to values of several kV/m. Such jumps of the electric field before the strong earthquakes is well documented experimentally (see, for example review of Rulenko, 2000).

The second part of the model, penetration of the electric field into the ionosphere is based on the series of publications of Kim et al. (1994), Kim and Hegai (1997) and in concise form is presented in Pulinets
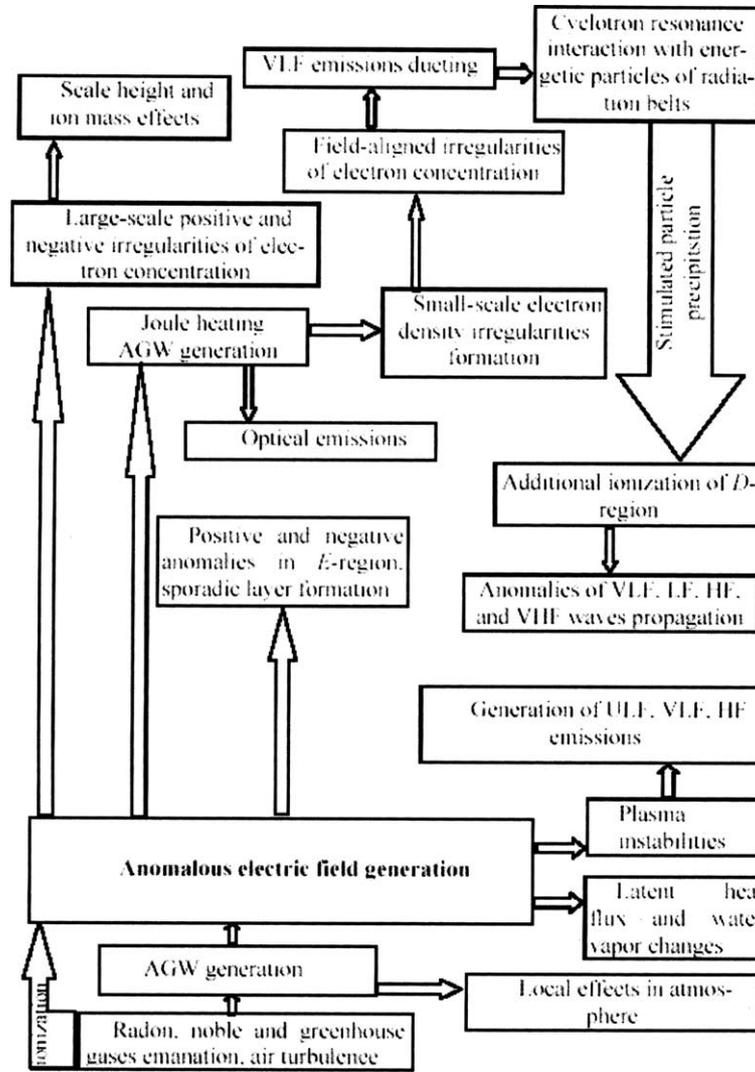
Fig. 4. Schematic presentation of the seismo-ionospheric coupling model.

et al. (2000). The calculations are based on the modified formulation of Park and Dejnakarintra (1973) who calculated the penetration of the thunderstorm cloud electric field into the ionosphere. This formulation was checked by many authors (Tzur and Roble, 1985; Rodger et al., 1998; McCormick et al., 2002) and was found
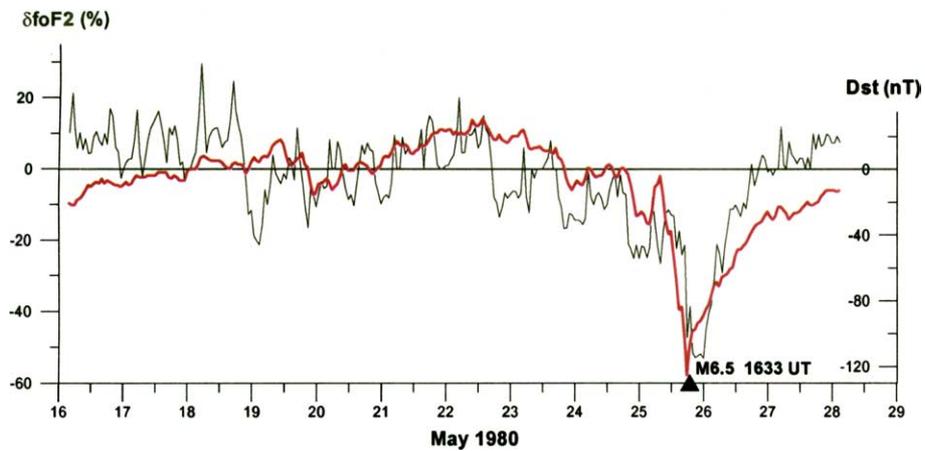

Fig. 5. Critical frequency deviation δf_oF2 (thin line, left axis) calculated from the point Arguelo ionospheric station data, and D_{st} index (thick line, right axis) for 16–28 of May 1980.

to be correct. From the model estimations of Pulinets et al. (2000) the minimum extension of electric field perturbation to cause effects in the ionosphere is of the order of 200 km. Such source with electric field intensity $\sim$1 kV/m will create within the ionosphere (in the E-region) the electric field perpendicular to the geomagnetic field lines of order of 1 mV/m which is sufficient to create the ionospheric irregularities due to particles $\mathbf{E} \times \mathbf{B}$ drift. Due to high electric conductivity along the

geomagnetic field lines the anomalous electric field will map into the upper layer of the ionosphere and magnetosphere creating the corresponding effects which is the third part of the model.

Effects of anomalous electric field at all ionospheric layers up to the magnetosphere were modeled by Kim et al. (1994), Kim and Hegai (1997), (Hegai et al., 1997), Pulinets et al. (2000), Pulinets et al. (2002) and registered experimentally. As not to overload the paper
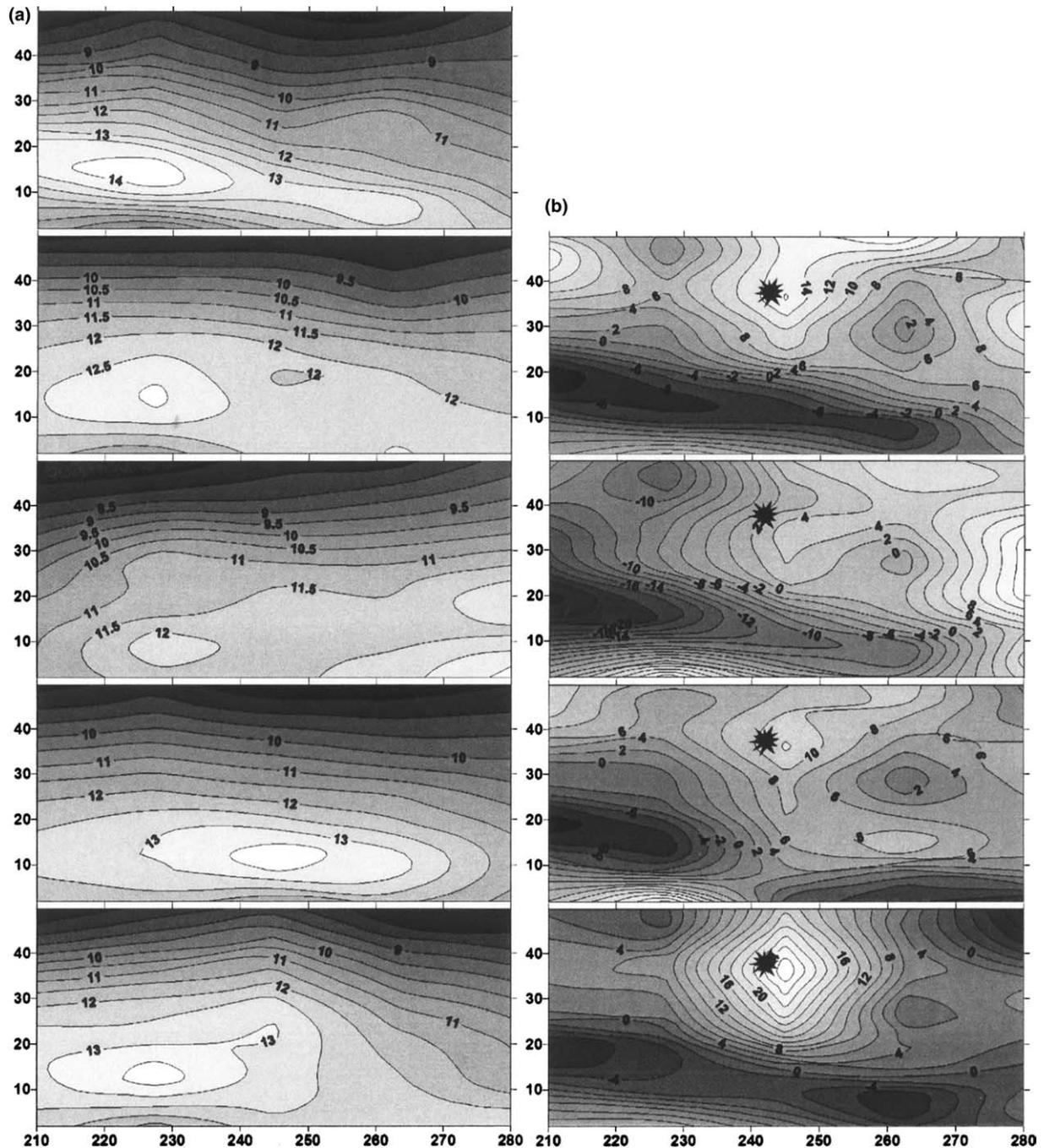

Fig. 6. (a) Absolute (f_oF2 distribution) LT maps for -15-16 LT. From top to bottom combined map for 15 and 19 May, 21, 22, 26 and 27 May. (b) The maps of the critical frequency deviation (in % relative to the top panel in the left column). From top to bottom 21, 22, 26 and 27 May. The epicenter position is shown by an asterisk.
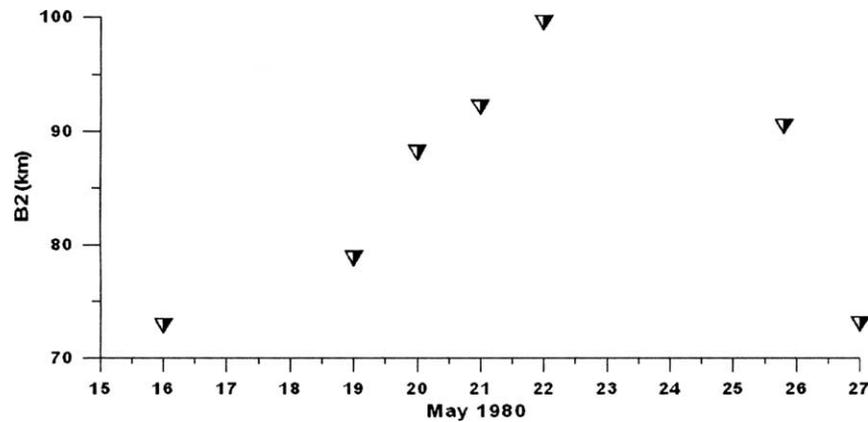
Fig. 7. Topside profile semi-thickness B2 calculated from topside profiles of Intercosmos-19 satellite for its position closest to the epicenter of impending earthquake presented as dependence of time (May 1980).

by seismic events we bring only one example of registration of ionospheric variability associated with seismic events which was registered around the time of a strong seismic swarm in California (May 1980) obtained from a combined analysis of Intercosmos-19 topside sounding data, and data from the Point Arguelo ionospheric station situated close to the earthquake's epicenter.

As in the case of the Chernobyl incident, a strong geomagnetic storm started practically simultaneously with the first shock of the May seismic swarm in the Mammoth Lake area in California when four severe seismic shocks with magnitude $M \geqslant 6.0$ and four shocks with $M \geqslant 5.5$ took place within two days (25–27 of May 1980). But several days before the geomagnetic situation was quiet. Nevertheless, the ionospheric concentration gradually started to diminish 5 days before the seismic shock (and BEFORE the magnetic storm which is seen in the Fig. 5), where the deviation of critical frequency from the monthly median (thin line) is shown together with the D_{st} index (thick line). Negative deviations start to be observed from 19 May regardless of the positive trend of the D_{st} index. Special attention should be paid to regular deviations on 22, 23 and 24 of May appearing every day at the same time which is one of the specific features of the ionospheric precursors of earthquakes (Pulinets et al., 2003). The spatial ionosphere modification is shown in Fig. 6 (left panel) for the area limited by 2–50°N, and 210–280°E, where maps of the critical frequency distribution are shown for several consecutive days (for which the satellite data were available). The right panel shows the percentage deviation of the critical frequency from the undisturbed condition. The combined map of 15 and 19 of May (the top map in the left panel of the Fig. 6) is taken as a background to calculate the deviation for consecutive days. The epicenter position is shown in the right panel maps as a black asterisk. One can see a peculiar structure close to the epicenter position with a clear positive anomaly on 21 and 27 May, and a negative deviation in the northern crest of

the equatorial anomaly. Pulinets et al. (2003) indicate the increase of the topside profile semi-thickness as a main signature of the ionospheric precursors of earthquakes. This parameter was derived using the Epstein approximation of topside profiles (Depuev and Pulinets, in press) for the satellite passes closest to the vertical projection of the epicenter. Its temporal dynamics is shown in Fig. 7 and clearly demonstrates the strong increase of the topside layer semi-thickness in completely quiet conditions and the return to normal values after the seismic shock.

6. Conclusions

Some experimental evidence was demonstrated to be conceivably connected with the effect of anomalous atmospheric electric fields in the ionosphere and not connected with solar or geomagnetic activity. These studies will be continued to obtain more solid evidence of the observed effects, but at least the theoretical calculations in the cited references indicate the possibility of the observed effects.

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