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Dynamics of the Near-Equatorial Ionosphere Prior to Strong Earthquakes

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Abstract—Dynamical changes in the near-equatorial ionosphere, observed in a few days prior to strong earthquakes with the epicenter located near the geomagnetic equator, are studied on the basis of vertical ionospheric sounding data. Several types of equatorial anomaly behavior prior to the earthquakes, depending on the local time interval considered, have been found: the anomaly may disappear and originate, or its form may be sharply distorted. It is shown that these variations occur not only in the *F*2-layer maximum but also within the entire layer. The parameterization of the electron concentration vertical profile in the topside ionosphere based on its approximation by the Epstein function made it possible to uncover a sensitive parameter (*B*2*u*) whose value increases in seismically disturbed conditions by a factor of ~1.5.

INTRODUCTION

The equatorial anomaly (EA) is a well-known phenomenon in the ionosphere, which manifests itself as a trough (or minimum) in the latitudinal distribution of the electron concentration $N_e(\varphi)$ in the vicinity of the geomagnetic equator. The largest amount of data on the structure and dynamics of the equatorial anomaly, collected with the help of satellite measurements, made it possible to reconstruct the latitudinal profiles of the ionospheric parameters. The equatorial trough in the latitudinal distribution of N_e in magnetically quiet conditions appears early in the morning, reaches its maximum in the afternoon, and then disappears gradually. Simultaneously with the trough degradation, the anomaly "crests" (maximum values of N_e) shift equatorward, and, thus, the normal latitudinal distribution of the ionization with a maximum at the equator is restored at night. The ratios of the *foF*2 values in the regions of EA maximum and minimum $d = foF2_{max}/foF2_{min}$ is, as a rule, used to determine the quantitative characteristics of EA. It is also known that EA is very sensitive to any variations in electrical fields of various origin. Recent studies of the quasi-static anomalous electric fields that appear in the seismic zones [Pulinets *et al.*, 1998b, 1999a], as well as the proved ability of these fields to penetrate to ionospheric heights [Pulinets *et al.*, 2000], encourage us to raise the question of the study of the impact of seismic electric fields on the equatorial ionosphere. In this paper, the ionospheric variability at equatorial latitudes related to seismic activity is studied on the basis of data on the electron concentration N_e in the ionosphere obtained with the help of topside sounding on board the Intercosmos-19 satellite [Pulinets *et al.*, 1991]. Data of other researchers are also included into the analysis [Depueva and Ruzhin, 1995; Liu *et al.*, 2000]. Pulinets *et al.* [1998a] showed that seismic ionospheric variations in N_e evidently depend on local time (LT); i.e., the sign of a deviation (positive or negative) from the undisturbed state depends on LT. The results obtained in this paper show that effects in the form of EA development due to seismic activity may manifest themselves in different ways: in some cases, the anomaly enhanced sharply against a background of EA that existed a few hours prior to an earthquake (i.e., the *d* value increased sharply). In other cases, an inverse picture was observed: a decrease in *d* to a complete disappearance of the "crests." Sometimes, EA was anomalously distorted: additional "crests" were formed.

EXPERIMENTAL DATA

N_e measurements during the vertical sounding of the topside ionosphere on board the Intercosmos-19 satellite (1979–1981) [Pulinets, 1989] were used in this paper. Since the orbiting parameters (inclination and period) were 74° and ~100 min, respectively, the local time when the satellite crossed the equatorial plane remained almost the same for several days. This made it possible to obtain ionospheric quasi-meridional sections at a longitudinal interval of ~25° for fixed LT instants. The time interval between the sounding seances was 64 s. During this time, the satellite orbited to ~3.6° in latitude. The latitudinal distributions of *foF*2 (or N_e) is analyzed for a series of strong earthquakes ($M > 5$) observed in the Pacific Ocean in magnetically quiet days. The data for various LT intervals were analyzed in order to search for a possible dependence of the modification of the low-latitude ionosphere on local time, detected by us earlier in the midlatitude region. To identify the effects on the parameters of the *F*2 layer maximum (N_mF2 and h_mF2) stimulated by seismic activity and to construct the maps of the vertical distribution (h, φ, N_e) along a fixed meridian, the $N_e(h)$ profiles for $h > h_mF2$ were calculated on the basis of the topside sounding ionograms. The whole N_e profile (100 km $\leq h \leq$ 1000 km) was constructed according to the method described by Nava *et al.* [2000]. Table 1 presents information on the earthquakes and the experimental data used in this study.

MODIFICATIONS OF EQUATORIAL ANOMALY FORMS PRIOR TO THE STRONG EARTHQUAKES

Figure 1a shows an example of EA development in the afternoon (1400–1500 LT) for the March 20, 1979, earthquake. Here and in all other figures, the earthquake latitude is shown by an arrow. It is clear that, in this period, EA remains insignificant for a long time prior to the earthquake ($\Delta t \sim$ 148 h). As the instant of the underground shock approaches ($\Delta t \sim -2.5$ h), the EA depth and width (the distance between the anomaly humps) increased significantly. For example, at the I = 0 latitude, the values of d are equal to 1.05, 1.2, 1.3, and 1.7 for the satellite passages $\Delta t \sim -148$, –6, –4, and –2.5 h prior to the earthquake, respectively. Figure 1b shows an example of EA development in morning hours (0330–0430 LT) for the May 24, 1980, earthquake. The *foF*2 data for the orbits passing almost over the epicenter ($\Delta\lambda \sim 3°$ and –6°) but long before the earthquake ($\Delta t \sim -84$ and –61.5 h) show no EA, whereas the anomaly is clearly defined in the data of the closest orbit ($\Delta t \sim -38.5$ h) to the earthquake onset. Figure 2 demonstrates an opposite situation when the EA "crests" disappear. Figure 2a shows data for each orbit in the evening (1730 LT) hours of the July 6, 1979, earthquake. At that time, EA had two evident "crests" and a trough about $\Delta t \sim 27$ and –3.5 h prior to the earthquake, but these orbits passed far from the seismic source. EA almost disappeared as the satellite approached (in space and time) the main shock of the earthquake ($\Delta\lambda \sim -3°$; $\Delta t \sim -2$ h). A similar situation was also observed according to data of a ground-based vertical sounding of the ionosphere (Fig. 2b). The *foF*2 hourly values along the chain of stations, located along the $\lambda \sim 126° \pm 20°$ meridian and in the geographic latitude range $\varphi \cong 2.7°$ S–62° N, were used for afternoon (1500–1600 LT) hours a few days prior the May 24, 1980, earthquake. The EA northern crest was observed in this region in the entire period considered, except for the last day before the earthquake, when it disappeared at $\Delta t \sim -24$ h (May 23, 1980). The analysis of the latitudinal variations in the total electron content (TEC), obtained by the system of GPS receivers at Taiwan Island for recent strong earthquakes that occurred at the island [Lie *et al.*, 2000], also confirms the conclusion that the northern "crest" disappears before strong earthquakes. The EA form was sometimes anomalously distorted. Figure 3 shows such an example of the EA distortion for the March 12, 1980, earthquake. At $\Delta t \sim -150$ h and $\Delta\lambda \sim -2°$, EA was pronounced normally (for this time of the day) and had two "crests" (the northern and southern) and a minimum at $I = 0°$. At $\Delta t \sim -52.5$ h, the EA northern "crest" increases slightly, and

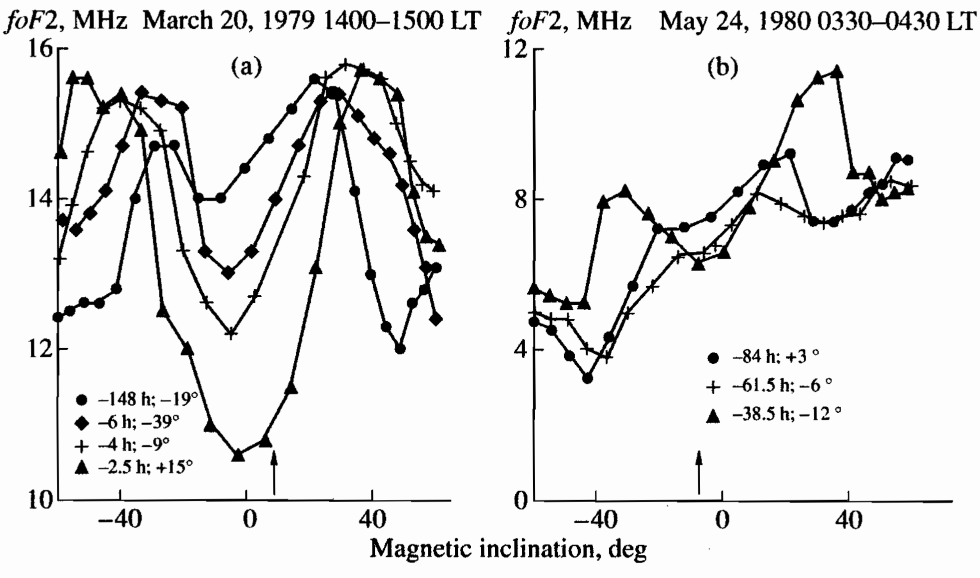

Fig. 1. Variations in the equatorial anomaly forms at the $F2$-layer maximum height according to Intercosmos-19 satellite data prior to the strong earthquakes in the vicinity of the geomagnetic equator: (a) the March 20, 1979, earthquake (1400–1500 LT) and (b) the May 24, 1980, earthquake (0330–0430 LT). The earthquake parameters are shown in Table 1. The earthquake latitudes are shown by arrows.

Table 1. Information on earthquake parameters and initial experimental data

Earthquakes							Intercosmos-19				
No.	Data	Position		Time UT, h, min	M	h, km	Data	Orbit	Time LT, h	Δt, h	λ, deg
		φ, deg	λ, deg								
1	March 20, 1979	7.6	126.6	08.53	5.3	147	March 14, 1979	226	1.6–2.6	–135	0
							March 19, 1979	299	1.6–2.6	–16.5	–15
							March 19, 1979	299	1.6–2.6	–13	+10
	March 20, 1979	7.6	126.6	08.53	5.3	147	March 14, 1979	226	14–15	–148	–19
							March 19, 1979	299	14–15	–4	–9
							March 19, 1979	299	14–15	–2.5	+16
2	July 6, 1979	3.6	126.6	10.07	5.1	68	July 5, 1979	1845	17–17.5	–27	–23
							July 6, 1979	1860	17–17.5	–3.5	–32
							July 6, 1979	1860	17–17.5	–2	–8
3	March 12, 1980	–15.2	–75.7	4.27	5.5	37	March 5, 1980	5389	17.5–18.5	–150	–2
							March 9, 1980	5446	17.5–18.5	–52.5	+12
							March 10, 1980	5461	17.5–18.5	–30.5	+1
4	May 24, 1980	3.6	126.5	8.24	5.2	69	May 20, 1980	6474	15.5–16.5	–96	–2.5
							May 20, 1980	6475	15.5–16.5	–96	+22
							May 21, 1980	6490	15.5–16.5	–72	+13
							May 22, 1980	6503	15.5–16.5	–66	–22
							May 23, 1980	6517	15.5–16.5	–27.5	–31
							May 23, 1980	6519	15.5–16.5	–24	+10
	May 24, 1980	3.6	126.5	8.24	5.2	69	May 20, 1980	6488	3.5–4.5	–84	+3
							May 21, 1980	6503	3.5–4.5	–61.5	–6
							May 22, 1980	6517	3.5–4.5	–38.5	–12
5	July 16, 1980	5.9	127.2	6.31	5.2	117	July 15, 1980	7286	17–18	–36.5	–7
							July 16, 1980	7301	17–18	–11.5	+8
							July 18, 1980	7331	17–18	+34.5	–10

Note: (1) Δt: the signs "–" and "+" correspond to the time before and after the underground shock, respectively; (2) $\Delta\lambda$: the signs "–" and "+" indicate that the satellite orbit passed eastward and westward from the earthquake epicenter longitude, respectively.

the southern "crest" disappears completely at $\Delta t \sim -30.5$ h and $\Delta\lambda \sim 1°$. The anomaly migrates into the Northern hemisphere, the trough appears at $I \sim 35°$ N, and the "crests" are formed at $I \sim 10°$ and 50° N.

Thus, we can state that, in a period of ~3 days to a few hours prior to the underground shock instant, various modifications of EA forms may be observed in the equatorial region. These effects may be conventionally divided into three groups: an increase (expansion) of EA, a disappearance of the "crests" (filling of the trough), and an EA distortion shown in the anomalous change in the through and "crests" locations.

MODIFICATION OF THE ELECTRON CONCENTRATION VERTICAL DISTRIBUTION PRIOR TO THE STRONG EARTHQUAKES IN THE EQUATORIAL IONOSPHERE

The analysis of the electron concentration vertical profiles $N_e(h)$, calculated from the ionograms of the topside ionospheric sounding over the regions of impending earthquake, shows that the ionosphere vertical structure is also affected by earthquakes. Figure 4 shows examples of such profiles calculated for quiet (curves *1*) and seismically disturbed (curves *2* and *3*) conditions: $N_e(h)$ profiles (a) for the July 16, 1980,

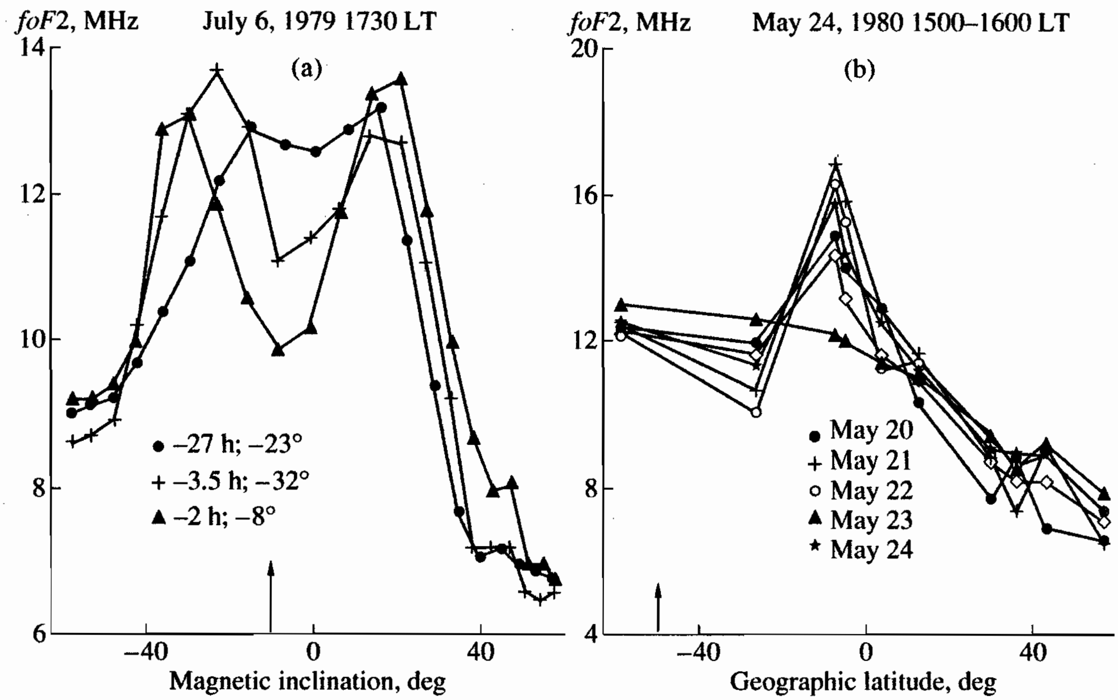

Fig. 2. Examples of the equatorial anomaly "crest" disappearance prior to the strong earthquakes: (a) the satellite data for the July 6, 1979, earthquake and (b) data of the ground-based vertical sounding of the ionosphere several successive days prior to the May 24, 1980, earthquake.

earthquake (φ = 11° N, λ = 143° E, 0500–0600 LT) and (b) for the July 06, 1979, earthquake (φ = 2°–5° N; λ = 133°–150° E, 1700–1800 LT). These two examples differ from each other in the opposite signs of the *foF*2 deviations under seismically disturbed and quiet conditions. Figure 4a shows that, in the morning hours prior to the earthquake, the *F*2-layer height increased by about 60 km (the layer ascended), and the concentra-

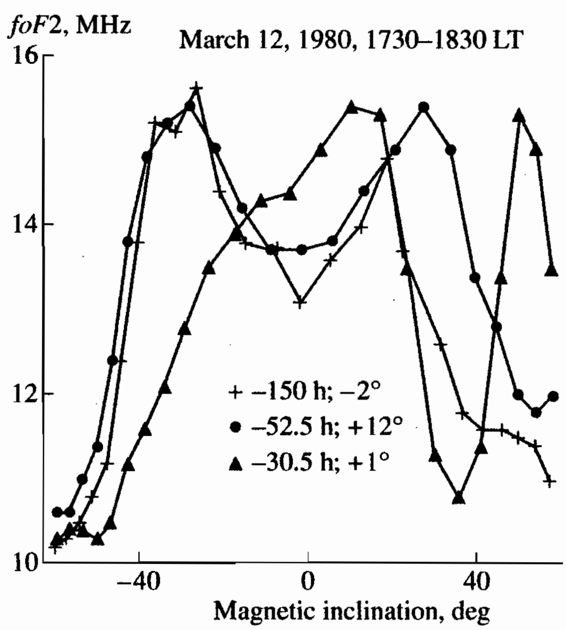

Fig. 3. Examples of the equatorial anomaly form distortion observed prior to the March 12, 1980, earthquake in South America.

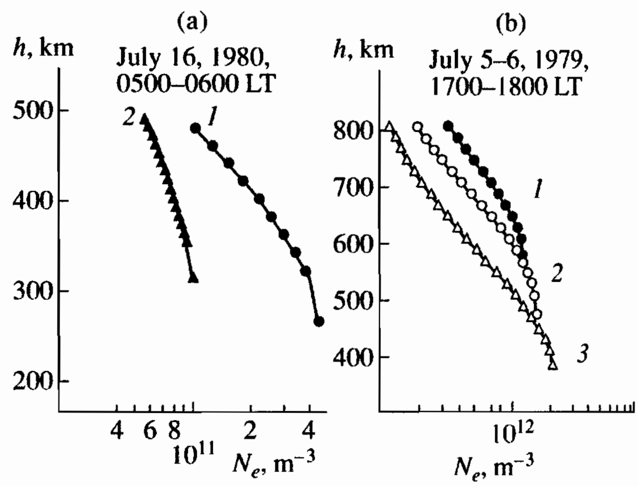

Fig. 4. Vertical profiles of the electron concentration prior to the strong earthquakes in the equatorial region. (a) The July 16, 1980, earthquake (0500–0600 LT, φ ~ 11° N, λ ~ 143° E); (*1*) quiet conditions; (*2*) seismically disturbed conditions. (b) The July 6, 1979, earthquake (1700–1800 LT, φ ~ 2°–5° N, λ ~ 133–150° E); (*1*) July 5, quiet conditions, Δ*t* ~ −27 h, Δλ ~ −23°; (*2*) July 6, seismically disturbed hours, Δ*t* ~ −3.5 h, Δλ ~ −32°; (*3*) July 6, seismically disturbed hours, Δ*t* ~ −2 h, Δ*t* ~ −6°.

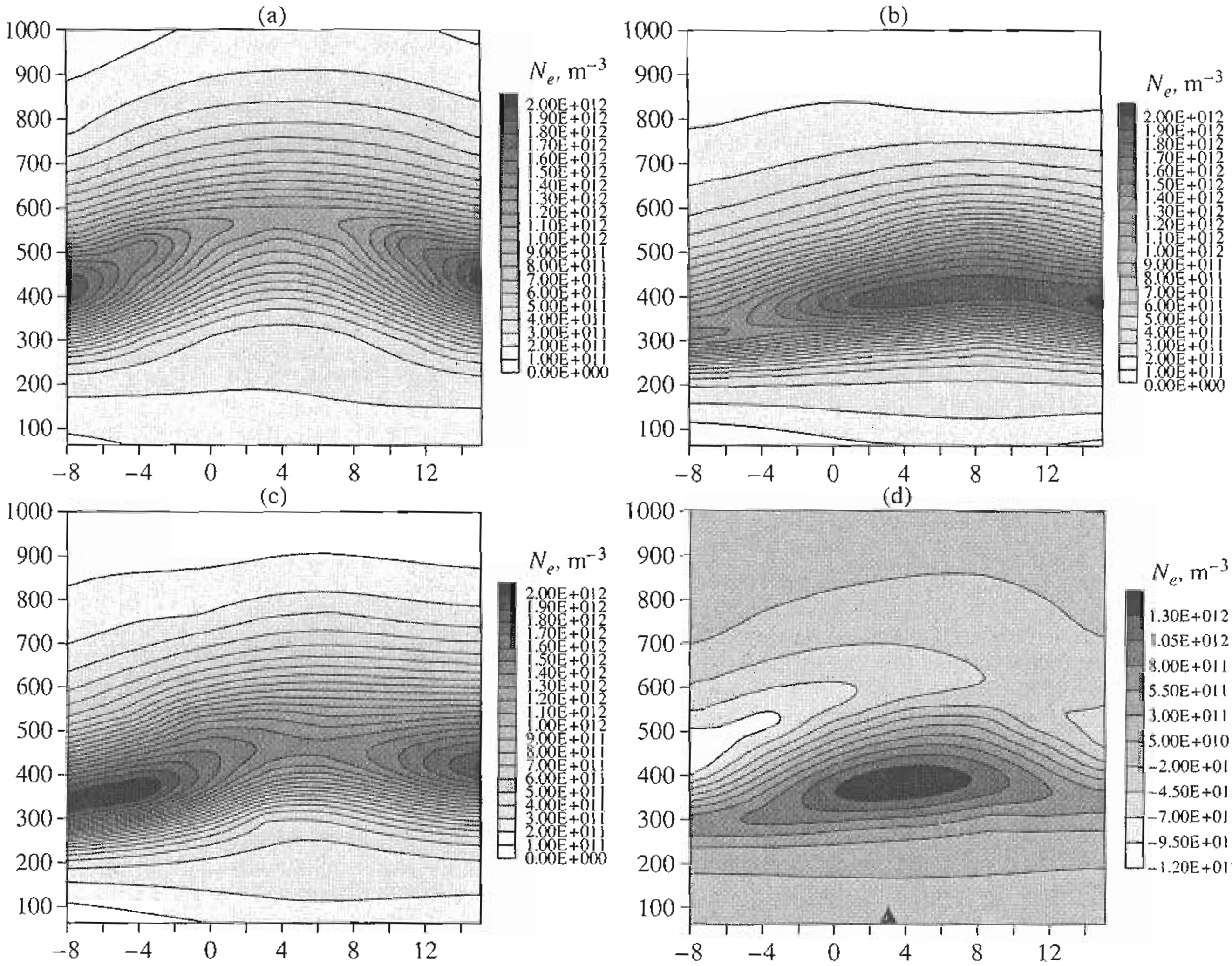

Fig. 5. Maps of the vertical latitudinal distribution of $N_e(h, I)$ for evening (1700–1730 LT) hours in the longitudinal sector over the source of the July 5, 1979, earthquake for the following conditions: (a) quiet hours on July 5, $\Delta t \sim -27$ h; (b) disturbed hours on July 6, $\Delta t \sim -3.5$ h; (c) disturbed hours on July 6, $\Delta t \sim -2$ h; and (d) the difference between (a) and (c), i.e. $\Delta N_e = N_e$(July 6) − N_e(July 5).

tion decreased by about 70%. An opposite picture is observed for the July 6, 1979, earthquake (Fig. 4b). The comparison between curves *1* ($\Delta t \sim -27$ h) and *2* ($\Delta t \sim -2$ h) shows that 2 h prior to the earthquake, the $F2$ layer descended by about 190 km, and the concentration increased by about 70%. However, we succeeded in discovering a common feature in the parameters of the N_e model profile for both cases. Radicella *et al.* [1995] showed that one can approximate the $N_e(h)$ profiles by the Epstein function

$$N(z) = 4.0Nm\frac{\exp\left(\frac{z}{B2u}\right)}{\left(1+\exp\left(\frac{z}{B2u}\right)\right)^2},$$

where $B2u$ characterizes the half thickness of the $F2$-layer topside part, which varies linearly with height: $B2u = B_0 + kz$, $z = h - h_{max}$. The calculations of the $N_e(h)$ profiles in both cases (a decrease and increase in $foF2$) show that the modified profiles have a significantly greater value of $B2u$ in seismically disturbed than in quiet conditions, possibly due to changes in the ion composition of the ionospheric F layer before an earthquake [Pulinets *et al.*, 1999b]. Table 2 shows the values of the parameters obtained by the Epstein formula for the two earthquakes considered (July 16, 1980, Fig. 4a, and July 6, 1979, Fig. 4b). Therefore, data of the topside sounding of the ionosphere may be parameterized and subsequently used to predict the place and time of an impending earthquake.

QUASI-TOMOGRAPHIC CONSTRUCTION OF THE IONOSPHERE VERTICAL STRUCTURE

The successive ionograms of the topside ionospheric sounding along satellite orbits make it possible

Table 2. Parameters obtained by the Epstein formula

Parameters	July 16, 1980		July 6, 1979		
	1	2	1	2	3
h_mF2, km	260	320	528	476	393
$foF2$, MHz	6.0	2.8	9.8	11.2	12.7
$B2u$	54.0	87.0	65.8	81.5	90.8
$k2u$	0.16	0.29	0.123	0.054	0.014

to calculate the $N_e(h)$ profiles for the topside part of the ionospheric $F2$ layer. On the other hand, the method described by Radicella and Zhang [1995] makes it possible to restore the entire vertical profile of N_e on the basis of its topside part available. Using these data, we managed to construct cross sections of the N_e vertical distribution for some longitudinal sectors. Figure 5 shows examples of such $N_e(h, I)$ cross sections for three instants prior to the July 6, 1979, earthquake (see also Table 2, Fig. 2a): (a) July 5, 1979, $\Delta t \sim -27$ h, (b) July 6, 1979, $\Delta t \sim -3.5$ h, and (c) July 6, 1979, $\Delta t \sim -2$ h. These figures indicate that the EA trough was filled up as the satellite approached the shock instant up to a complete disappearance of the "crests" and appearance of one maximum at the equator. To make the process more evident, we found the difference between the (a) and (c) sections, i.e. the $\Delta N_e(h, I) = N_e(h, I)_{6.07} - N_e(h, I)_{5.07}$. The cross section $\Delta N_e(h, I)$ is shown in Figure 5d, where the vertical reconstruction of the ionization and formation of the electron concentration maximum over the source zone are evident. The vertical extent of this maximum is about 200 km (from 300 to 500 km).

CONCLUSIONS

The analysis of topside sounding ionograms obtained on board the Intercosmos-19 satellite indicated a strong modification of the equatorial anomaly structure prior to the strong earthquakes. Depending on local time, EA may both increase (deepen) or attenuate (be filled up) as compared with its state in undisturbed conditions. Cases of EA form distortion, when the trough and "crests" shifted along the latitude, were also observed. EA was modified not only at heights of the $F2$-layer maximum but also in the entire topside ionosphere, which is a result of the vertical reconstruction of the near-Earth plasma distribution over the regions of impending earthquake. The half thickness of the topside part of the $N_e(h)$ profile of the $F2$ layer ($B2u$) is the most important parameter indicating that EA is modified prior to an earthquake. The value of this parameter increases in seismically disturbed conditions by a factor of about 1.5. The EA modification results obtained on the basis of the Intercosmos-19 satellite data are confirmed by data of the ground-based vertical sounding of the ionosphere and GPS measurements of the total electron content.

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