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Spatial–Temporal Characteristics of Large Scale Disturbances of Electron Density Observed in the Ionospheric F-Region before Strong Earthquakes

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Abstract—The spatial dimensions and temporal dynamics of large scale disturbances of electron density in the ionospheric F-region during the preparatory phase of destructive earthquakes are estimated. The most appropriate data (as far as the moments of satellite passages are concerned) were selected out of more than 300 investigated cases. In order to demonstrate effects at different latitudes, the cases of high-latitude (Alaska), mid-latitude (Central Italy), and low-latitude (New Zealand) earthquakes were considered. Using the data of external vertical sounding of the ionosphere performed by the *Alouette-1* and *Interkosmos-19* satellites together with the data of vertical sounding of the ionosphere by ground-based instruments, we get for the first time with reasonable accuracy the spatial characteristics of precursors in the ionosphere. It is shown that seismic ionospheric disturbances are strongly time-dependent before the beginning of the main shock. Seismic ionospheric disturbances are generated weakly several days before the first shock, but at that moment the disturbed region is located not above the epicenter, but rather a little displaced from it. As the moment of the earthquake approaches, the disturbance covers more and more space; moreover, its value also increases. Several hours after the shock the disturbance migrates in the reverse order. Under some conditions, the disturbances may appear not only above epicenter regions. They can be transferred along the magnetic field lines into conjugate regions in the opposite hemisphere.

INTRODUCTION

It is now clear that seismic activity undoubtedly reveals itself in the Earth's atmosphere at ionospheric heights ($h < 1000$ km). The results concerning ionospheric precursors of earthquakes were obtained during a period of data accumulation and generalized in monograph [1]. Since that time, the interest of the scientific community in the reaction of the ionosphere to the preparatory phase of earthquakes has been ever increasing and the region within which this reaction is sought is becoming considerably wider. Two main lines of research are currently being developed: the study of particular (individual) events and the retrieval of some average characteristics of seismic activity effects at the heights of the Earth's ionosphere. Although an interrelation between the dynamics of lithospheric processes and variations of ionospheric parameters is justified both theoretically [3] and statistically [4], it is rather difficult to separate these disturbances from other effects (meteorological or cosmic). Numerous studies of seismic ionospheric disturbances using the data of vertical sounding of the ionosphere before strong earthquakes ($M > 5$) [2] have shown that different ionospheric parameters are disturbed at ionospheric heights. These data together with the data of seismic monitoring might be used for making predictions of earthquakes. Our more than ten years of investigations (see, for example, [3–11]) have allowed us to isolate the main

Earthquake characteristics and initial data

No.	Date	Epicenter		Time		M	Region	Data
		φ, deg	λ, °E	UT	LT			
1	Mar. 28, 1964	61.1	212.4	03:36	17:36	9.2	Alaska	Ground-based stations, *Alouette-1* satellite
2	June 19, 1980	–30.0	178.5	08:34	20:26	6.4	Kermadec Island	Ground-based stations, *Interkosmos-19* satellite
3	Nov.23, 1980	41.1	15.4	18:34	19:34	6.7	Italy	Ground-based stations, *Interkosmos-19* satellite

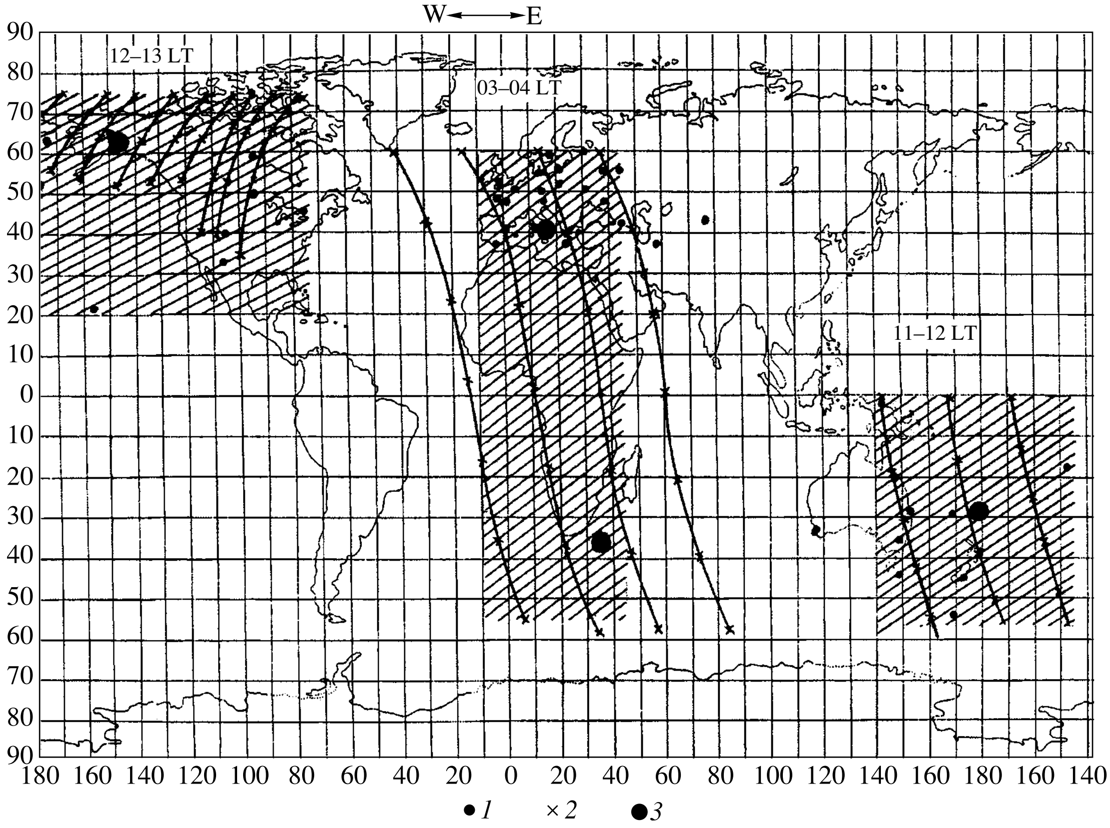

Fig. 1. A scheme of arrangement of (*1*) ground-based stations for vertical sounding of the ionosphere, (*2*) spacecraft orbits, and (*3*) coordinates of epicenters for the three earthquakes. The hatched regions were investigated: the Alaska earthquake ($\varphi \approx$ 20°–75°N, $\lambda \approx$ 80°–120°W); the Italian earthquake ($\varphi \approx$ 20°–60°N, $\lambda \approx$ 350°–45°E); and the Kermadec earthquake ($\varphi \approx$ 0°–55°S, $\lambda \approx$ 140°–210°E).

morphological features of the ionospheric precursors of earthquakes:

—the ionospheric precursors are variations of the ionospheric plasma density (deviations from its undisturbed value) observed from five days to a few hours before a seismic shock;

—the sign of variations may be either positive or negative;

—the duration of variations of one sign is small and does not exceed 4–6 h;

—the threshold of the possibility to separate seismic ionospheric variations in the ionosphere is determined empirically and they begin to be visible for earthquakes with magnitudes >5–5.5;

—basically, the seismic ionospheric variations have an amplitude of 15–25%, but in some particular moments may be greater than 100%;

—the sign and shape of seismic ionospheric variations depend on the local time;

—for strong earthquakes the dimension of a disturbed region of the ionosphere at the height of the F2 layer maximum is about 30° both in latitude and longitude;

—the location of a disturbed region maximum in the ionosphere does not always coincide with the vertical projection of the epicenter of the future earthquake. Up to the present all investigations of electron density variations associated with the earthquake preparatory phase were most frequently performed using either the data of ground-based vertical sounding or the data of external sounding (satellites). As is known, each of the methods has some limitations. It is impossible using the data of sounding from ground-based stations to determine the spatial configuration of a disturbance in the ionosphere. In return, the temporal dynamics is known both for the disturbance (with respect to the moment of a seismic shock) and for the ionosphere (its behavior relative to the local time). Satellite sounding is limited by the fact that a satellite passes through the region under investigation for a short time interval. If the ascending and descending legs of an orbit are taken, then for a selected event (we adopt a time interval of several days before earthquake) there are only two intervals of the local time that correspond to the time sector where the satellite orbit currently resides. At the same time, with a satellite one can easily determine the spatial configuration of a disturbance in the ionosphere. Combining the data of both methods, one can determine both the temporal characteristics (ground-based vertical sounding) and the spatial localization (satellite vertical sounding) of seismic ionospheric effects with a better accuracy. It is just this combination of both methods of measurements that is used in this work in order to analyze the data of seismic ionospheric variations in the F-region.

The most interesting cases were selected from a variety of available data (more than 300 earthquakes). The appropriate location of the satellite orbit and the existence of ionospheric observatories in the region of an earthquake were used as selection criteria. In addition, we endeavored to demonstrate the behavior of the ionosphere at different latitudes. For this purpose we have chosen the Alaskan high-latitude earthquake in 1964, one of the strongest earthquakes that ever happened on Earth; the mid-latitude earthquake in Central Italy (there is a rather well-developed network of ground-based stations for vertical sounding in Europe); and the low-latitude earthquake in New Zealand (the network of Australian ground-based ionosondes was used for supporting the satellite data in this case). The information about the earthquakes considered is presented in the table.

We would like to emphasize that this work does not pretend to give a comprehensive analysis of the problem of ionospheric precursors of earthquakes. Our aim was to clarify general features of large-scale variations of the electron density in the ionospheric F-region and to determine their temporal dynamics and dimensions.

INITIAL DATA

The method used by us for separating the anomalous behavior of the ionosphere associated with the seismic activity of the Earth using the data of ground-based and space-borne instruments for sounding the ionosphere has been discussed earlier many times (see, for example, [3–11]). Still, the problem of reliable detection of ionospheric precursors is among the most important, since the ionosphere parameters are very sensitive to any changes of both natural and artificial origin. Special attention should be paid to the problem of distinguishing the effects associated with magnetic storms and disturbances of seismic origins. As is shown in [6], the disturbances caused by magnetic storms have a planetary character, while the disturbances of seismic origin are local and have much less magnitude. In addition, the data of mass-spectrometric observations aboard satellites show [12] that an increased abundance of light ions is observed above the regions of preparing earthquakes, while during magnetic storms the average mass of ions in the F-region increases due to the decreasing O/N_2 ratio. This gives yet another method to discern variations in the ionosphere associated with earthquakes.

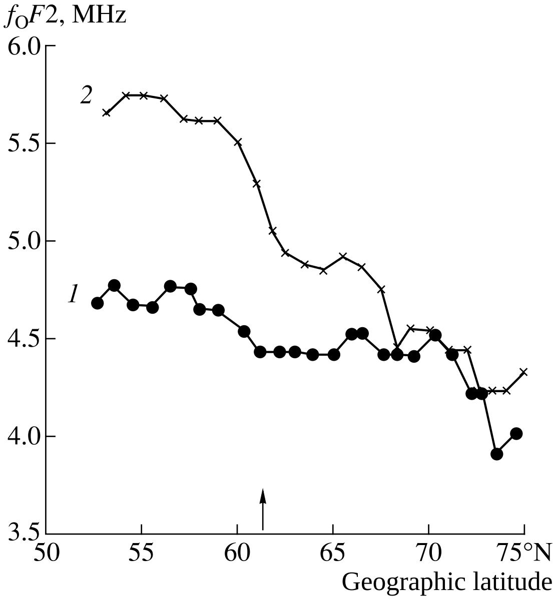

Fig. 2. Comparison of latitudinal distributions of f_0F2 for two neighboring orbits of the *Alouette-1* satellite on March 27, 1964: curve *1* $\Delta\lambda = -20°$, $\Delta t = -30.5$ h; and curve *2* $\Delta\lambda = +5.5°$, $\Delta t = -29$ h. An arrow shows the earthquake latitude.

In order to separate the variations in the F2 region using the data of ground-based vertical sounding, the median value (monthly or running) or some distributions for five or ten of the most quiescent days of the current month were taken most frequently as the quiescent background. In the case of satellite measurements one has to use the latitude and longitude distributions obtained for the investigated region under magnetically quiet conditions as a quiescent background. As in our previous investigations, the measurements of electron density in the maximum of the $F2$ (f_0F2) region obtained from the network of ground-based stations of vertical sounding for the corresponding region and the data from the *Alouette-1* (1964) [13] and *Interkosmos-19* (1980) [14] satellites were used as the initial data. As usual, the disturbance degree was estimated by the deviation from the quiescent background: $\delta f_0F2 = (f_0F2\text{cur} - f_0F2\text{med}) \times 100/f_0F2\text{med}$, %. Figure 1 shows the arrangement of stations for vertical sounding and trajectories of spacecraft orbits. Since any satellite could pass over the epicenter region only twice a day at moments not coinciding with the moments of sounding (regular ionospheric sounding is performed once every 15 min or every hour), the data of ground-based stations were interpolated between neighboring values at the moment of the satellite passage. In order to exclude temporal gradients (the quantity f_0F2 has a well-pronounced diurnal variation), only narrow longitudinal intervals ($\lambda \approx \pm 30°$) were considered.

RESULTS AND DISCUSSION

The Alaskan earthquake of March 28, 1964, gave the first impetus to scientific investigations of seismic effects on the Earth's atmosphere. A number of papers were published that reported on the response of the ion-

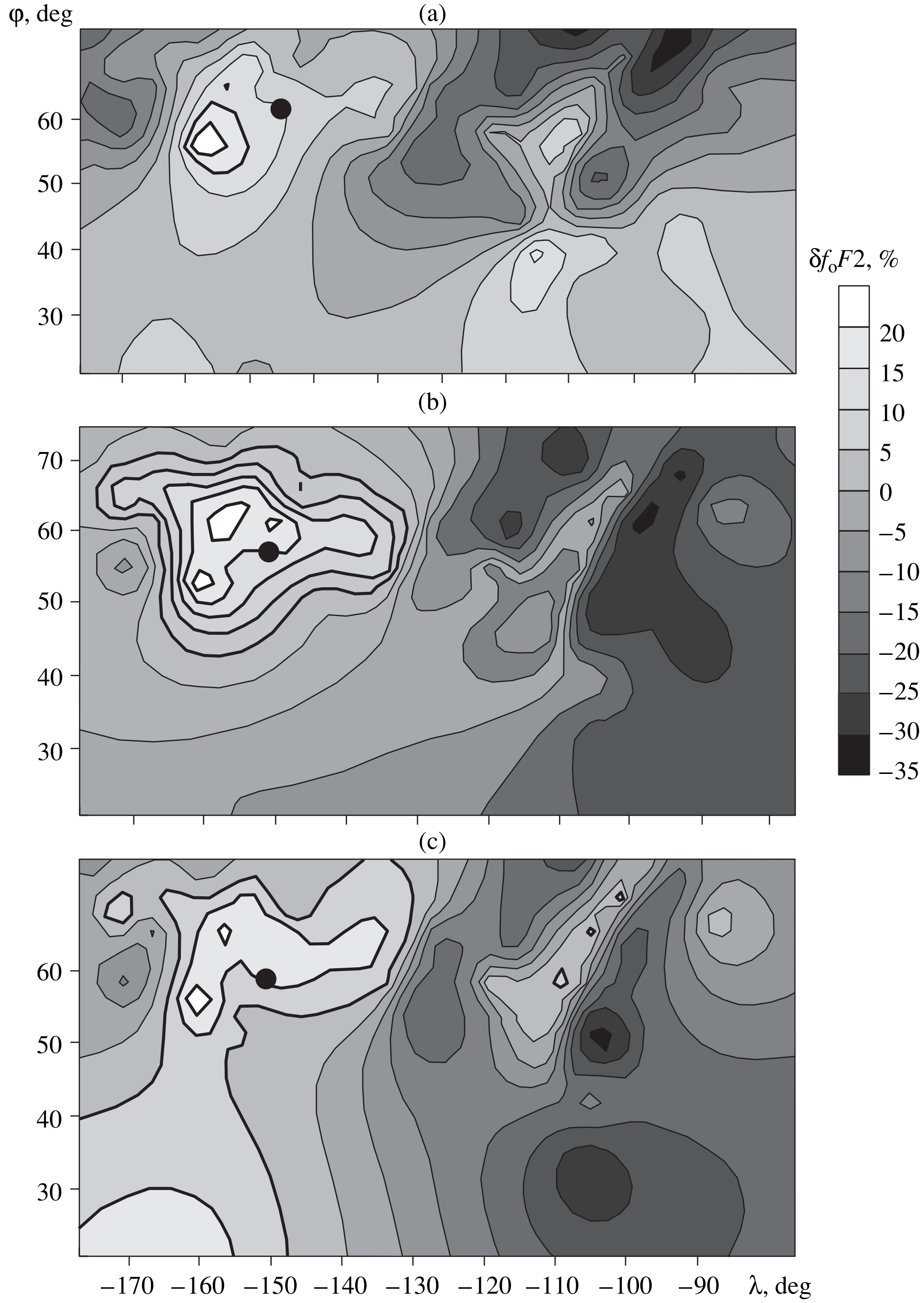

Fig. 3. Maps of latitudinal–longitudinal distribution of δf_0F2 for noon (12–13) hours of local time during the preparatory period of the earthquake: for $\Delta t \approx -29$ h (Fig. 2a), for $\Delta t \approx -4...-6$ h (Fig. 2b), and after the earthquake for $\Delta t \approx +18$ h (Fig. 2c). Black circles mark the earthquake epicenter.

osphere to this earthquake [15, 16]. However, there is no loss of interest in this event to the present. Rich experimental material concerning the ionosphere near the epicenter region was available (there were ≈12 stations for vertical sounding and the data of the *Alouette-1* satellite), and this allowed us to analyze in great detail the behavior of the ionosphere several hours before and after and during this earthquake. The geophysical situation from March 15 to March 30, 1964, was the following: magnetically quiet days were on March 17–18 and 27–29; there was a disturbance on March 22–25, moreover, a magnetic storm occurred at 08:00 UT on March 22. The analysis of f_0F2 diurnal variations using the data of all stations in the region showed that for several days (March 22–25) negative disturbances were observed in the ionosphere, which were traced in the data of all stations, both high-latitude (for example, Providence Bay, φ = 64.4° N) and low-latitude (Maui, φ = 20.83° N). The nearest stations to the epicenter are Anchorage (R = 133 km) and College (R = 423 km). More detailed results of data analysis for these stations of vertical sounding are presented in [11].

The *Alouette-1* satellite passed over the epicenter region during the night (22–23 LT) and day (12–13 LT) hours. Unfortunately, the data on f_0F2 in the night were very scarce, so only the data of the day sector were analyzed. The daytime data were available for March 17, 19, 23, and 27–29. These data allowed us to consider the situation in the ionosphere for five time intervals: quiet days of the month (March 18–19); the main phase of the magnetic storm on March 23; and before the main underground shock, at $\Delta t \approx -30.5$ h (March 27) and $\Delta t \approx -6$ h (March 28), and after it, at $\Delta t \approx +18$ h (March 29). Even a simple comparison of f_0F2 values for subsequent satellite orbits on March 27 showed their large discrepancy. Figure 2 presents the latitude distributions of f_0F2 for this day: curve *1* corresponds to $k_p = 2_-$, UT = 20:46, LT = 12:17, $I = 78°$, $\lambda = -127.4°$, $\Delta\lambda = -20°$, $\Delta t = -30.5$ h; curve *2* corresponds to $k_p = 1_-$, UT = 22:31, LT = 12:15, $I = 74°$, $\lambda = -154.1°$, $\Delta\lambda = +5.5°$, $\Delta t = -29$ h. One can see that the density in the F2 region sharply increased by ~30% when the satellite was crossing the region of the future earthquake. In this case, the maximum increase was observed not at the latitudes of the epicenter, but ~5° to the west of it.

Thus, using the entire body of data (satellite and ground-based experiments), the maps of latitudinal–longitudinal distributions of δf_0F2 were plotted for the time periods mentioned above. During the magnetic storm, negative disturbances (decreasing electron density, "f_-) appear practically in the entire region of the considered longitudes, while the effects associated with the earthquake (Fig. 3) are very local and accompanied by increasing electron density ("f_+") by 20–25%. The disturbance associated with increasing f_0F2 values changes with time and depends on the time before the beginning of the main shock. For example, it is clearly seen that the ionosphere reacts to the given earthquake (Fig. 3a) already at $\Delta t \approx -29$ h. At this time, a small region of increased values of f_0F2 (~15–20%) appears, but this region is displaced a little to the southwest of epicenter. Further on, in $\Delta t \sim -6...-4.5$ h (Fig. 3b), the region of "f_+" encompasses a major part in space, and the amplitude of disturbances is much higher ($\delta f_0F2 \sim$ 35%). Finally, the electron density is still increased after the earthquake, $\Delta t \sim +18$ h, but its region is again displaced, this time to the northeast. Thus, the data of ground-based and satellite vertical sounding of the ionosphere allowed us to construct a qualitative picture of the latitudinal–longitudinal anomalous variations of f_0F2 associated with the Alaskan earthquake. We succeeded in demonstrating that the ionosphere reacted to this earthquake in advance, already at $\Delta t \approx -29$ h.

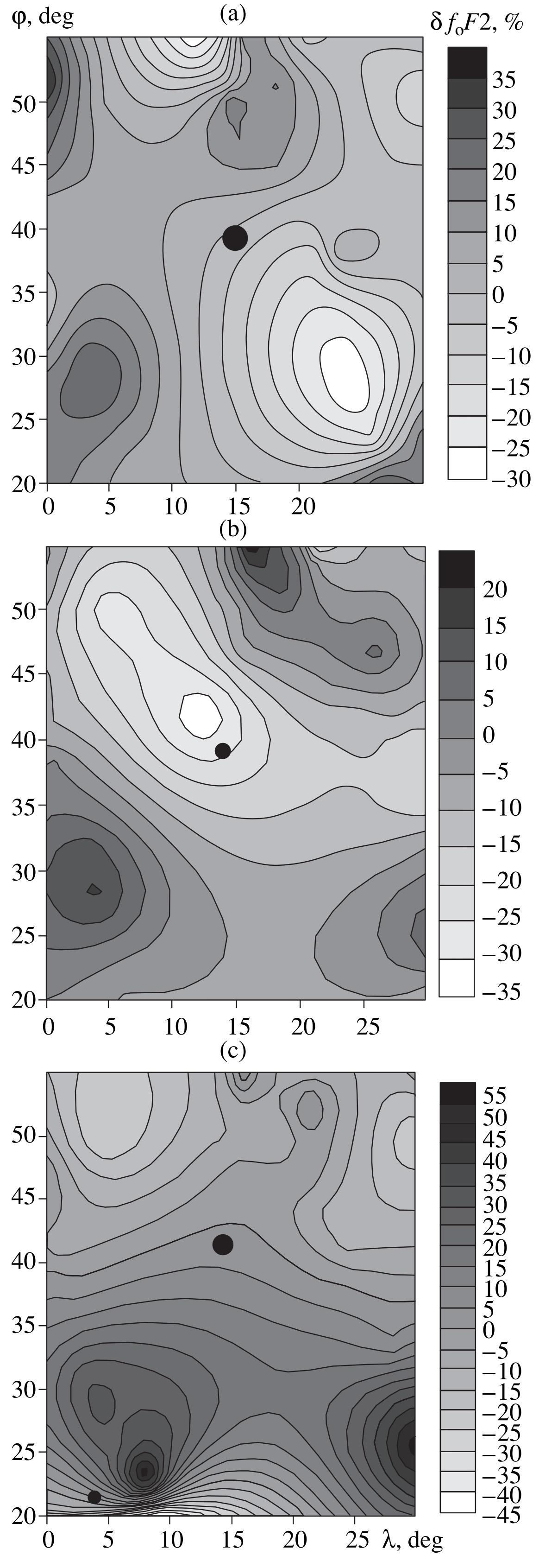

Fig. 4. Maps $\delta f_0F2(\varphi, \lambda)$ during morning hours (03–04) for the Italian earthquake: $\Delta t \approx -64$ h; (b) $\Delta t \approx -40...-42$ h; (c) $\Delta t \approx +6$–8 h.

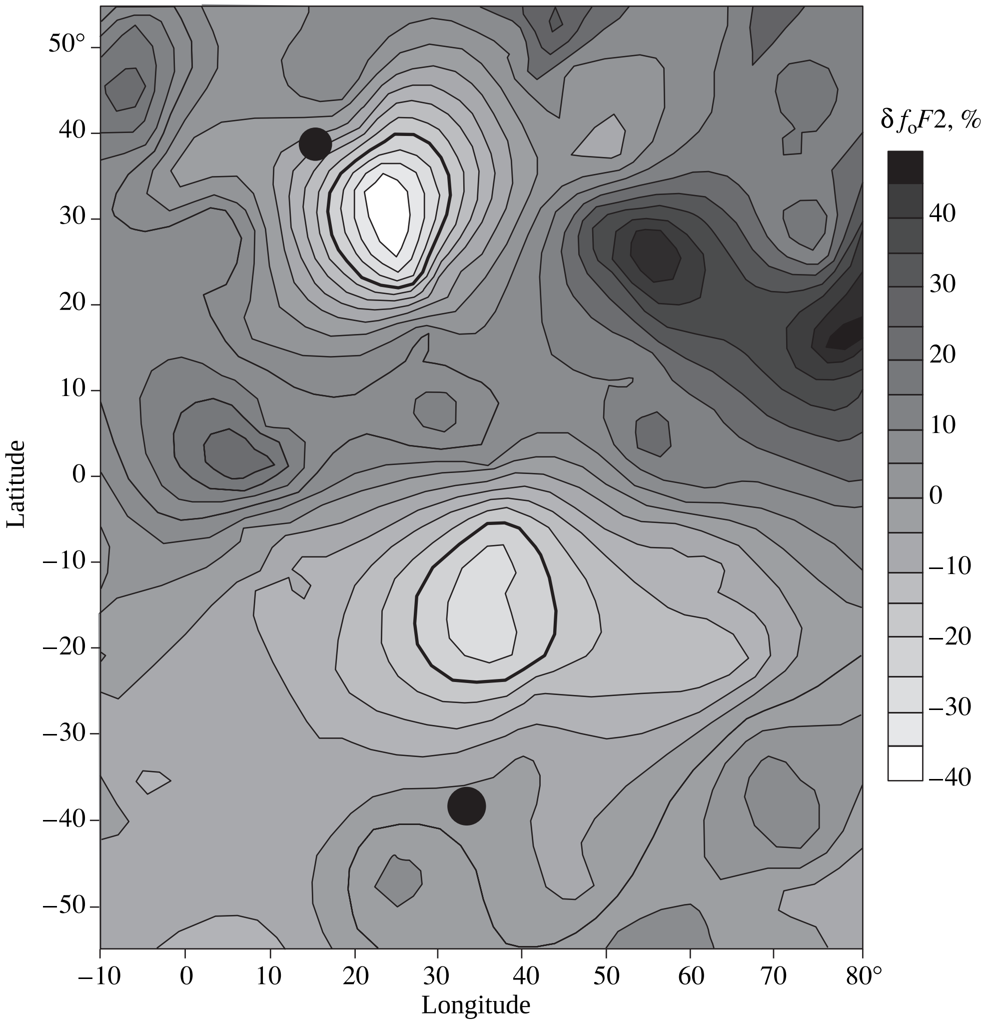

Fig. 5. Latitudinal–longitudinal manifestation of a seismic ionospheric precursor in the epicenter region and its magnetically conjugated point during early morning hours for $\Delta t \approx -64$ h before the Italian earthquake from the data of the *Interkosmos-19* satellite.

The reaction of the ionosphere to the Italian earthquake (November 23, 1980) was analyzed by us previously in [7]. A new element in the present study is an attempt to use simultaneously the data of ground-based and satellite vertical sounding. As in the case of the Alaskan earthquake, the density of ionospheric data was also high: the measurements of ground-based stations for vertical sounding in the European sector and the data of the *Interkosmos-19* satellite. This allowed us to get a latitudinal–longitudinal distribution of the ionospheric disturbance associated with the Italian earthquake. For plotting the maps of $\delta f_0F2(\varphi, \lambda)$ the time was chosen for when the satellite data were available. During this period the satellite passed over the epicenter at 03–04 h LT for $\Delta t \approx -112, -87, -64, -42, -40$, and +9 h; and at 18–19 h LT for $\Delta t \approx -120, -96, -72$, and –1.39 h. The anomalous decrease and increase of f_0F2 ("f_-" and "f_+") were observed during the early morning hours and evening hours, respectively. The maps $f_0F2(\varphi, \lambda)$ plotted using the data of November 18–19 were taken as the quiescent background. The maps $\delta f_0F2(\varphi, \lambda)$ for morning hours were plotted for three different time moments: $\Delta t \approx -64$; –40…–42.5, and +6...+8 h (Fig.4). One can see that the "cloud" of a decreased density gradually began to be formed already 2.5 days ($\Delta t \approx -64$ h) ahead of the main shock, but in the region displaced by ~10° in both latitude and longitude to the south of the epicenter. Later, at $\Delta t \approx -40...-42$ h, this "cloud" was displaced toward the epicenter and "spread" in the northwestly direction. Roughly 6–8 h after the main shock, the state of the ionosphere in the epicenter region was stabilized.

Recently, it was shown in [9, 17] that ionospheric effects might appear not only in the epicenter region, but also in the magnetically conjugated point in the opposite hemisphere. Using only the data of the *Interkosmos-19* satellite, we succeeded in constructing a map $\delta f_0F2(\varphi, \lambda)$ for the morning sector at $\Delta t \approx -64$ h in the entire region of latitudes from 60°N to 60°S, i.e., including the magnetically conjugated region (Fig. 5).

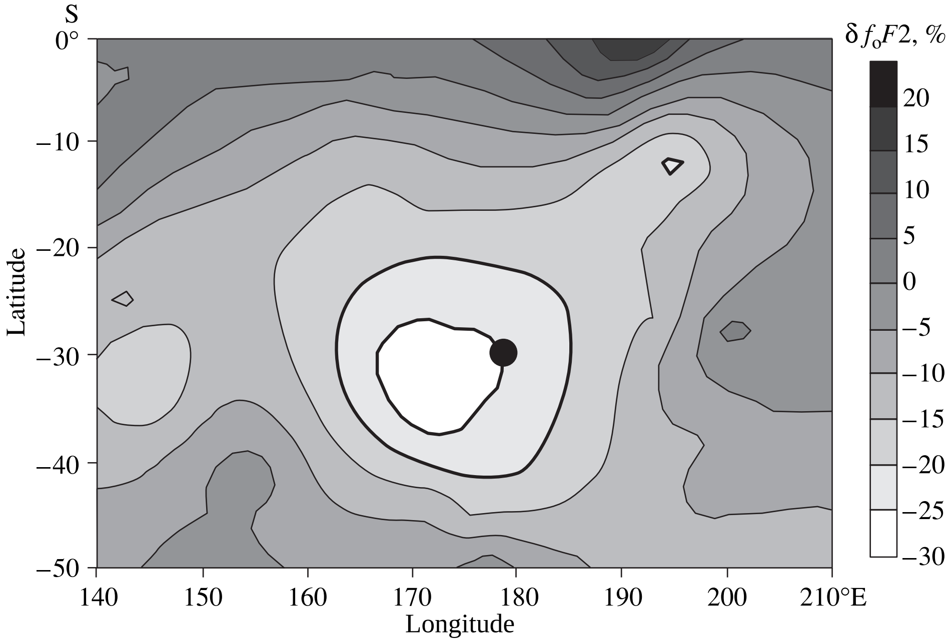

Fig. 6. A map $\delta f_0F2(\varphi, \lambda)$ for the earthquake on June 19, 1980, during noon hours (11–12 LT) for $\Delta t \approx -8...-9$ h from the data of ground-based and satellite vertical sounding of the ionosphere.

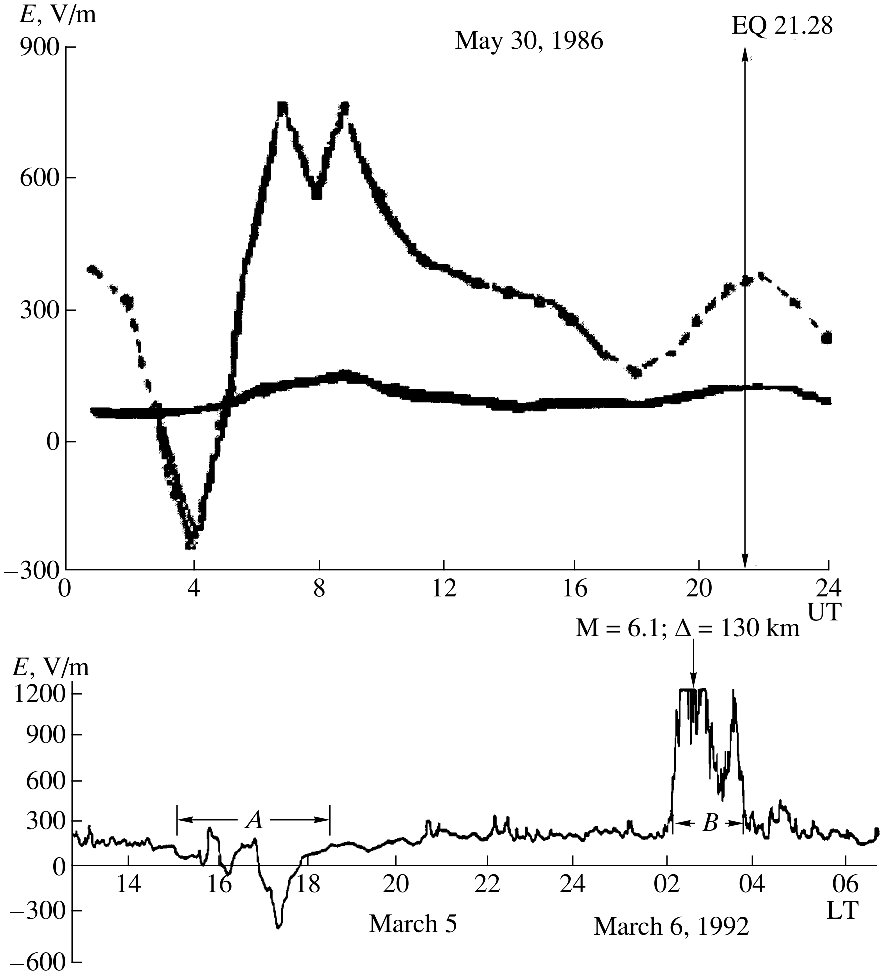

Fig. 7. Examples of electric field measurements before large earthquakes presented in [24, 25].

If the epicenter was located at a point with the geographic coordinates $\varphi = 40.8°\text{N}$, $\lambda = 15.3°\text{E}$, then the conjugated point had the coordinates $\varphi = 35.3°\text{S}$, $\lambda = 34.5°\text{E}$. It is clearly seen that, if the maximum effect of decreasing f_0F2 ($\delta f_0F2 \approx -30\%$) above the epicenter was observed at the point ($\varphi \approx 30°\text{N}$, $\lambda \approx 25°\text{E}$), the same effect was recorded in the conjugated point ($\varphi \approx 25°\text{S}$, $\lambda \approx 37°\text{E}$). The disturbance in the epicenter region was displaced ~10° to the southwest relative to the epicenter. The same displacement, but in the northeastly direction, was observed in the magnetically conjugated region.

The data from ground-based stations for vertical sounding in the Australian region and from the *Interkosmos-19* satellite for daytime hours (11–12 h LT) were available for the earthquake (Kermadec Island) on June 17, 1980. The satellite data were obtained for $\Delta t \approx -56$ h (June 17); $\Delta t \approx -33.5$ h (June 18); $\Delta t \approx -9$ h (June 19); and $\Delta t \approx +14.5$ h (June 20). The variations of f_0F2 obtained by satellite and ground-based data on June 17, 1980, were used as a quiescent background. In this case, a seismic ionospheric precursor is visible only for $\Delta t \approx -9$ h as a decrease of f_0F2 and no anomalous disturbances were traced in the ionosphere on other days. Figure 6 shows a map of the latitudinal–longitudinal distribution δf_0F2 for $\Delta t \approx -9$ h. The parameters of the earthquake on June 19 were similar to those of the Alaskan earthquake, but the reaction of the ionosphere had the opposite sign. In both cases, the reaction of the ionosphere to the earthquake during the daytime was considered, but the sign of the disturbances was opposite. For example, in the case of the Alaskan earthquake we have $\delta f_0F2 \approx +35\%$ as a precursor for $\Delta t \approx -6...-4$ h, while $\delta f_0F2 \approx -30\%$ for Δt $-9...-7$ h for the earthquake on June 19. Apparently, this discrepancy is explained by some difference in the local time. In the case of the Alaskan earthquake our results correspond to 11–12 h LT, but the time is 12–13 h LT for the event of June 19. These results agree well with the results of [10], where it is shown that the precursor's sign ("f_+" or "f_-") strongly depends on the local time. As far as localization in space is concerned, the results of the analysis for the June 19 event are very similar to those for the Alaskan earthquake. The "cloud" with decreased values of f_0F2 is a bit displaced to the west of the epicenter.

SIGN REVERSAL OF SEISMIC IONOSPHERIC VARIATIONS

The existence of both positive and negative seismic ionospheric variations bewildered researchers for a long time. Different physical mechanisms were proposed, but their large number only caused fair distrust and critics of the scientific community. In our opinion, a unified and consistent approach to describing the observed phenomena has been found in the last few years [18]. It is based on the influence on the ionosphere of an anomalous quasi-static electric field above the regions of would-be earthquakes. This idea is not new and appeared in the 1930s [19, 20]. The capability of the atmospheric electric field to penetrate into the ionosphere has been discussed in the scientific literature for a rather long time. A calculation for the process of penetration of thundercloud electric fields into the ionosphere was performed in [21]. In [22], the calculations were made that we used later for modeling the seismic–ionospheric coupling in [18]. It should be mentioned that attempts to calculate the penetration of the seismic electric field into the ionosphere were made in other works too, for example, in [23]. However, the anisotropy of atmospheric conductivity appearing above 60 km was not taken into account in [23], which prevented the authors from reaching the correct conclusions.

In the calculations of [18], the experimentally measured electric field values of ~1000 V/m were used. The most important point of this discussion is that the change of an electric field sign leads to a changed sign of variations in the ionosphere, as is really observed in the experiment. Figure 7 presents some examples of electric field measurements before large earthquakes demonstrating the effect of a changing field sign [24, 25]. Allowing for the fact that electric field variations experimentally observed have a sporadic character, the observed variations in the ionosphere should be changed in accordance with the strength and sign of the anomalous electric field.

As for the displacement of variations in the ionosphere relative to a vertical projection of the future epicenter, two factors are important. First, the electric field is transferred into the ionosphere along the magnetic field lines; therefore, in most cases the disturbed region is shifted to the South from the epicenter projection in the northern hemisphere (to the north in the southern hemisphere). Second, according to the mechanism of electric field generation described in [3, 18], the configuration of the spatial electric charge above the Earth's surface considerably depends on turbulent processes in the surface air; this charge may be transported by the wind to large distances, which has also been mentioned in the literature.

CONCLUSION

For the first time, the dynamics of the origination, spatial dimensions, and localization of ionospheric disturbance of seismic origin at heights of the ionospheric F-region ($h \approx 250$–350 km) are demonstrated using the data of simultaneous vertical sounding of the ionosphere from ground stations and satellites for three of the strongest earthquakes. The dynamics of the disturbance development depending on the time of the main shock is traced. Several days before the earthquake, a weak "cloud" of disturbance is formed in the ionosphere. This happens not strictly above the vertical projection of the epicenter. The nearer the time of the first shock (for example, $\Delta t \approx -6...-4$ h), the larger the area encompassed by the “cloud” moving to the epicenter (the intensity of the disturbance also increases). In a few hours after the shock the “cloud” migrates in the opposite direction. Under certain conditions, the seismic ionospheric disturbance may appear not only in the epicenter region, but also may be transferred along the magnetic field lines into the magnetically conjugated region.

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