Geomagnetism and Aeronomy, Vol. 42, No. 3, 2002, pp. 344-349. Translated from Geomagnetizm i Aeronomiya, Vol. 42, No. 3, 2002, pp. 360-365.
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Variations in the Ionospheric *F2* Region Prior to the Catastrophic Earthquake in Alaska on March 28,1964, According to the Data of the Ground-Based Stations of the Ionospheric Vertical Sounding

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Received
February 27, 2001; in final form, October 2, 2001

Abstract—The variations in the ionospheric *F2.* region prior to the catastrophic earthquake in Alaska on March 28, 1964, are analyzed. The evolution of the spatial distribution of the critical frequencies in the Alaska region a few hours prior to the earthquake, when the disturbances of the critical frequency in the vicinity of the epicenter were maximum has been studied. It is shown that, at least, a few hours prior to the earthquake, specific regional disturbances were observed in the ionosphere both near the epicenter of the impending earthquake (~100 km) and at a considerable distance from it (-1000-1500 km). It has been found that, according to the data of Anchorage ground-based station of ionospheric vertical sounding located at a distance of 124 km from the earthquake epicenter, in the vicinity of this epicenter, the amplitude of the disturbed daytime values *offoF2* is maximum and reaches -25% 4.5 h prior to the main underground shock.

1. INTRODUCTION

A large body of the experimental data has been accumulated by the present, on the basis of which ionospheric disturbances prior to earthquakes were repeatedly analyzed [Fatkullin *et al,* 1991; Gokhberg *et al,* 1988; Zelenova and Legen'ka, 1989; Zelenova *et al,* 1991]. Some monographs are also dedicated to this problem *[Atmospheric,* 1999; Liperovskii *etal,* 1992]. However, it is always very difficult to distinguish among the experimental data a typical "portrait" of the ionospheric anomalies related to the impending earthquake. The difficulties in revealing ionospheric precursors of earthquakes is caused by various factors, among which we should mention the following ones. First, the amplitudes of the ionospheric anomalies observed prior to earthquakes are, as a rule, small and lie within the ordinary diurnal variability of the ionosphere. Second, the anomalies should be filtered out of ionospheric disturbances caused by other factors, mainly, of a solar and magnetospheric origin. Besides, to relate reliably ionospheric variations to the impending earthquake, we should know all peculiarities of the regional behavior of the ionosphere in the geographic zone considered under quiet and disturbed conditions. The latter is a separate problem.

In many papers, the data on the /^2-layer critical frequencies *foF2* are analyzed in order to detect ionospheric earthquake precursors prior to a particular seismic event. Zelenova and Legen'ka [1989] studied a variability *offoF2* using the 15-min measurements during several days before, during, and after the Moneron earthquake of September 5, 1971 (the epicenter geographic coordinates (p_e = 46.5° N; $A_{,e}$ = 141.1° E, the shock time 1735 UT, the magnitude *M* = 7.2) and the Kamchatka earthquake of September 5, 1971 ((p_e = 56.0° N, \ = 165.0° E, the shock time 1455 UT, *M* = 5.4). A stable increase in the evening (1800-2200 LT) values *offoF2* was demonstrated at the stations located in the epicenter zone a few days prior to the earthquake. The maximum values *offoF2* were detected immediately prior to the earthquake. In a similar way, Zelenova *et al.* [1991] obtained that prior to the Spitak earthquake of December 7, 1988, the background values of *foF2* also increased at night (2200^0400 LT) one-two days prior to the earthquake, and this effect had a pronounced regional character. Fatkullin *etal.* [1991] analyzed a series of earthquakes, before which specific ionospheric variations were also observed one or two days prior to the main shock. In this case, the variations were also of a regional character, and their typical horizontal scale was 1000-1500 km. Legen'ka *et al.* [1995] also analyzed ionospheric effects of the strong *(M* - 6.9) Italian earthquake of November 23, 1980, using the data of the ground-based stations of vertical sounding of the ionosphere (VSI) and the topside sounding on board the Intercosmos-19 satellite. It was found that the precursor effects in the ionosphere appear at night (2200-0400 LT) one-two days prior to the main shock. In this case, a critical frequency decreased by 1-1.5 MHz, and the maximum effect was observed southeastward of the epicenter. The spatial distribution of the critical frequency deviations A/0F2 from the median

The VSI stations, whose data were used in an analysis and their geographic coordinates and distances to the earthquake epicenter

Station name	Geographic longitude X, E, deg	Geographic latitude (p, N, deg	Distance to the epicenter along a great circle arc *R*, km
Adak	183.4	51.9	2090
Provideniya Bay	186.6	64.4	1365
Barrow	203.2	71.2	1192
College	212.0	64.9	423
Anchorage	210.1	61.2	124
Resolute Bay	265.1	74.7	2536
Churchill	265.8	58.8	2899
Narssarssuaq	314.6	61.17	4904

foF2 values, obtained at the VSI stations five days prior to the strong earthquake in Abruzzo (Central Italy, May 7, 1984, $M = 5.8$) was presented by Pulinets *et al* [1988]. A two-focus picture of the disturbance was discovered, the focuses of the negative and positive deviations being displaced westward and southward, respectively, from the epicenter of the future earthquake. The maximum deviations were 20 and 30%, respectively.

The studies mentioned above considered seismo-ionospheric effects in the midlatitude *F2* region. Pulinets *et al.* [1991] discussed in detail the low-latitude response of the ionosphere to the seismic phenomena in the ionospheric *F2* region related to five strong earthquakes, occurred in the summer of 1980 on the islands located eastward of Australia and New Guinea, based on the data of the ground-based and topside sounding on board the Intercosmos-19 satellite. It was shown that the disturbances observed begin 2-3 days prior to the earthquake, reach its maximum 1-1.5 days before the underground shock, and, sometimes, are observed after it. The maximum electron concentration values N_mF2 in the ionospheric *F2* layer differ by 60% from the median values, and the typical horizontal dimensions of the disturbance region exceed 15°, i.e., 1500 km.

Several authors [Davies and Baker, 1965; Leonard and Barnes, 1965; Row, 1966] considered the ionospheric phenomena related to the catastrophic Alaskan earthquake of March 28, 1964 ($<p_e = 61.1°$ N, $\backslash_e$ = 147.6° W, the shock time 0336 UT, $M = 8.4$). They analyzed mainly ionospheric wave disturbances that occurred shortly after the shock. The theoretical calculations by Row [1967] fairly satisfactorily describe the ionospheric disturbance observations [Davies and Baker, 1965] in the framework of the formalism of linear acoustic gravity waves propagating from the earthquake epicenter after the shock.

In this paper, we analyze the large-scale spatial distribution of the critical frequencies *foF2* in the Alaskan region and the evolution of this distribution pattern during several hours before the main shock, based on the VSI stations.

2. EXPERIMENTAL DATA

The table shows the hourly data of the ground-based VSI stations on the F2-layer critical frequency *foF2,* which were used to analyze the events related to the earthquake considered.

Since (see, for example, Davis [1969]) $N_mF2 = 1.24 \text{ x } l0^4(foF2)^2$, where N_mF2 is the electron concentration (in cm$\sim^3$) in the maximum of the ionospheric *F2* layer, and/oF2 is the critical frequency of the ordinary wave (in MHz), the electron concentration distribution at the F2-layer maximum may be interpreted in terms of the critical frequency measured directly at the VSI stations. Below, we will consider only the values of the critical frequency, since it is unambiguously related to N_mF2.

Besides these data, we used the daily mean values of the *AE* index and the solar radiation flux at A, = 10.7 cm ($F_{10\ 7}$) in order to control the geophysical situation in the time periods considered. The experimental values of all the values considered were obtained from the World Data Center (WDC) via the Internet (http://www.wdc.rl.ac.uk).

3. GEOPHYSICAL SITUATION

The *AE* index did not exceed 200 nT four days prior to the earthquake, the epicenter of which was located at $<p_e = 61.1°$ N, and decreased to 33 nT immediately before the earthquake, which corresponds to the very quiet magnetic situation. At the same time, the variation in the solar radiation flux $F_{10\ 7}$ did not exceed 5% of its mean value. Thus, ionospheric anomalies due to solar and magnetospheric factors can hardly be observed in this period. We can make this conclusion more convincing by comparing the data of the Anchorage and Narssarssuaq VSI stations, located, respectively, at the shortest ($R \sim 100$ km) and large ($R \sim 5000$ km) distances from the future earthquake epicenter. Since both stations are located at almost equal geographic latitudes (9 = 61.2° N and 61.17° N for Anchorage and Narssarssuaq stations, respectively), they have similar condi-

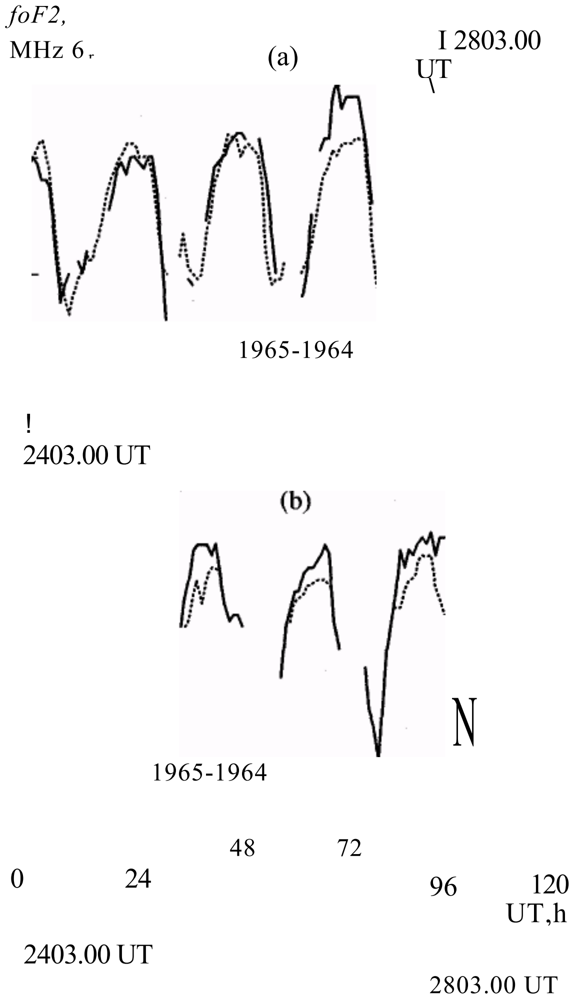

Fig. 1. Diurnal variations in the critical frequency *foF2* (a) at Anchorage station during March 24-28, 1964 (solid curve) and March 24-28, 1965 (dotted curve); (b) the same but for Narssarssuaq station. Vertical line (dashes) marks the underground shock instant on the UT axis.

tions of illumination during a day and, to a certain degree, similar diurnal behavior of the critical frequencies, at least, in the daytime, other conditions being equal. Such a comparison is performed below.

4. DEVIATION OF THE DIURNAL BEHAVIOR OF *foF2* FROM THE CONTROL BEHAVIOR AT ANCHORAGE PRIOR TO THE EARTHQUAKE

As follows from the table, Anchorage is the closest station to the earthquake epicenter. Therefore, it is natural to expect that possible ionospheric anomalies related to the impending earthquake will be most pronounced in the critical frequency diurnal variation at this station. Figure la shows the diurnal variations in the critical frequency *foF2* at Anchorage between March 24 and 28 of 1964 (solid curve) and 1965 (dotted curve). Vertical dashed line marks the shock instant at the UT axis. This period in 1965 was chosen as a reference one for comparison, because, at that time, the values of AE-index and solar radiation flux $F_{10\ 7}$ almost coincide **and significant seismic events were absent in the Alaskan region** ((p = **55.0°** N-75.0^0 N; X = **185.0° E-265^0 E) as well as in such a period of 1964 before the shock.** It is evident that, at 1300 LT (2300 UT) a day before the earthquake, the critical frequency *foFl* is by 0.6 MHz higher than such a value in the control curve. In the same period of the following day, namely approximately 4.5 h prior to the main shock, this excess is maximum (1.2 MHz), i.e., is equal to 26% (which corresponds to the ~60% excess in terms of electron concentration).

Figure Ib shows, in the same denotations, the diurnal behavior of the critical frequency at Narssarssuaq, located, as noted before, at almost the same latitude as Anchorage but very far (~5000 km) from the epicenter of the Alaskan earthquake. It is clear that disturbances were really not observed in this period of both 1964 and 1965. Figure 1 clearly indicates that **the general character of the** *foF2* **diurnal behavior (seen in both curves) is similar** to such a behavior, observed at Anchorage in 1964 prior to the earthquake.

Thus, we can conclude that the ionospheric disturbance observed at Anchorage is actually of a regional character and may be related to the impending earthquake as its short-term (days-hours) precursor. This conclusion is supported by the fact that, at College station, which is more remote from the earthquake epicenter *(R* ~ 400 km) than Anchorage, the character of the *foF2* diurnal variations is similar to that of such variations at Anchorage, though the maximal deviation from the control curve is here slightly smaller (~1 MHz), possibly, due to the longer distance of this station from the epicenter.

5. GLOBAL DISTRIBUTION AND EVOLUTION OF THE CRITICAL FREQUENCIES IN THE ALASKAN REGION A FEW HOURS PRIOR TO THE EARTHQUAKE

We follow the general evolution of the critical frequency distribution in the Alaskan region prior to the earthquake from 2000 to 2300 UT on March 27,1964, i.e., up to the instant when the critical frequency at Anchorage reached its maximum approximately 4.5 h before the main shock (5.8 MHz as compared to 4.6 MHz in the control curve in 1965). For this purpose, we put the critical frequencies *foF2,* measured at the stations shown in the table (except for Narssarssuaq located outside the region considered) at successive instants 2000, 2100, 2200, and 2300 UT, on a geographic map and draw a surface of *foF2* values as a function of geographic longitude (A,, deg) and latitude (9, deg). The map of equal *foF2* values (isolines) obtained in such a way reflects a spatial distribution of the ionospheric plasma at the UT instants chosen above, and we obtain a sequence of "UT-snapshots" of the ionosphere in the longitude-latitude coordinates.

Figure 2a shows the results of the procedure described above. The earthquake epicenter position is marked by a filled circle in each of four panels. It is clear that, in the panel corresponding to 2000 UT, the isoline picture comprises a system of curves aligned with the longitude axis. In this case, the/oF2 gradient is directed mainly equatorward from the pole, i.e., along the latitude axis. Such a plasma distribution agrees with the common character of plasma distribution at F-region heights: an increase in the plasma concentration from the pole toward the equator because of a decreasing solar zenith angle (with decreasing latitude) and increasing illumination. The region shown in geographic coordinates occupies the longitudinal sector from 185° to 265° E. The instant 2000 UT corresponds to 0800,1600, and 1000 LT at the left-hand and right-hand boundaries of the distribution pattern and at the epicenter longitude, respectively.

A successive distortion of the initial picture is traced distinctly in consequent "snapshots" and is most pronounced in the last one. The latter demonstrates clearly that, in the epicenter region, the values and spatial gradient of *foF2* are close to their maxima. The characteristic horizontal scales of the disturbance zone are 1000-1500 km. Figure 2b shows for comparison two panels similar to those shown in Fig. 2a. The top panel shows the initial distribution of the/<?F2 isolines at 2000 UT on March 27, 1964, and the bottom panel shows the critical frequency isolines at 2300 UT on March 27, 1965. It is evident that the critical frequency distributions in both panels are qualitatively similar, i.e., the general concentration distribution at F-region heights remains unchanged: it grows with decreasing latitude (under daytime conditions) because of increasing illumination. We note that, at 2300 UT, the left- and right-hand boundaries of the region correspond to 1100 and 1700 LT, respectively, i.e., we can state that the region in question is located in the zone of maximum illumination. Unfortunately, we failed to draw control figures for the previous UT hours of 1965 because of the gaps in the data from reference stations at those instants.

6. RESULTS AND DISCUSSION

An analysis performed made it possible to reveal specific variations in the value and character of the critical frequency/0F2 distribution both in the vicinity of the impending earthquake epicenter (~100 km) and at a significant distance (-1000-1500 km) from it one day (or at least a few hours) prior to the catastrophic earthquake, occurred in Alaska on March 28, 1964. First, these results confirm the data obtained earlier for other regions: **considerable characteristic spatial (thousand km) and temporal (day) scales of manifestation of the earthquake ionospheric precursors** [Fatkullin *et al,* 1991; Gokhberg *et al.,* 1988; Legen'ka *et al,* 1995; Pulinets *et al,* 1991, 1998; Zelenova and Legen'ka, 1989; Zelenova *et al,* 1991]. Second, the results obtained demonstrate for this specific case a presence of **most significant variations in the ionosphere in the vicinity of the epicenter (a few hundred kilometers) several hours prior to the shock.** Third, based on these results, we can trace the evolution

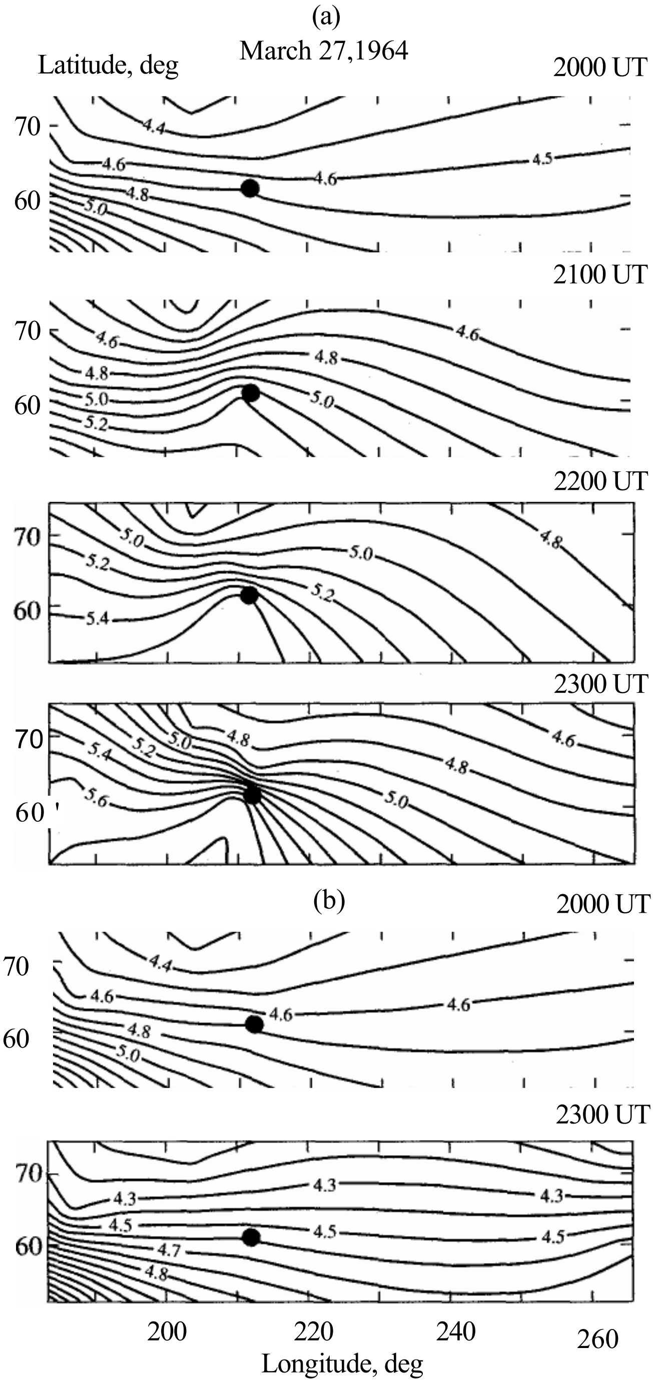

Fig. 2. Isolines of the critical frequency *foF2* (MHz) for (a) successive instants 2000, 2100, 2200, and 2300 UT on March 27, 1964, in the Alaskan region in geographic coordinates longitude-latitude; (b) the same but for 2000 UT on March 27, 1964 (the top panel) and 2300 UT on March 27, 1965 (the bottom panel). Filled circle marks the position of the March 28,1964, earthquake epicenter.

of the seismo-ionospheric disturbances on a time scale of the order of 1 h during the first hours prior to the earthquake in the entire **high-latitude ionospheric region** over Alaska in the **form of "UT-snapshots" of the ionosphere.** We succeeded to perform such a procedure, apparently, for the first time.

The important methodical difference of this analysis from the previous studies [Fatkullin *et al.,* 1991; Legen'kaef *al.,* 1995; Pulinets *etai,* 1991,1998; Zelenova and Legen'ka, 1989; Zelenova *et al.,* 1991] is that we did not use as control undisturbed values of *foF2* any averaged values (medians, running means, etc.). Such a possibility appeared because of an uncommon coincidence of the geophysical situation in the period considered in 1964 and 1965: the absence of even week geomagnetic disturbances and almost complete coincidence of the background activity of the auroral electrojet and solar irradiance. Thus, a double control was carried out: the coincidence of the undisturbed diurnal behavior in 1964 and 1965 and the usage (as control values) of the/oF2 values for the same period in 1965 or the diurnal behavior of *foF2* in 1964 in the quiet period nearest to the appearance of the disturbances related to seismic activity (see Fig. la).

The large-scale character of the variations in the ionosphere, which follows from the results obtained, is possibly due to a regional peculiarity of the earthquake source region, which is located in the belt of compression (subduction) of two giant tectonic platforms: Pacific and North-American [Dedeev and Kulikov, 1994]. Here, we note that the same large dimensions of the region of disturbance caused by the seismic events were obtained by Fatkullin *et al.* [1991], Gokhberg *et al.* [1988], and Pulinets *etal* [1991].

The physical mechanism of formation of the ionospheric disturbances prior to earthquakes is still to a certain degree unclear, since it is explained in a series of hypotheses [Liperovskii *et al.,* 1992]. If we assume that *large-scale* planetary waves are generated prior to earthquakes (as was supposed by Molchanov and Hayakawa [1998], who detected disturbances in the ionospheric *D* region before a series of seismic events on the basis of the phase measurement of VLF signals propagating near seismo-active zones), it is natural that the seismo-ionospheric variations (1000-1500 km) are large-scale. On the other hand, if we relate ionospheric disturbances prior to an earthquake to a generation of considerable quasi-static electric fields on the Earth's surface of an epicentral region (as was assumed by Kim *et al.* [1994]), then, as the estimates show, the values of these fields on the Earth's surface and typical horizontal scales should be a few hundreds V/m and of the order of 1000 km and more, respectively. In this case, the fields with a magnitude of a few mV/m, which can give the/oF2 distribution pattern distortions similar to those shown in Fig. 2a for the period of a few hours, will be observed in the ionosphere. Concerning the "electrostatic" hypothesis, we should note a pioneer work by Moore [1964] (not dealing directly with ionospheric studies). This researcher first recorded a **magnetic disturbance with an amplitude of lOOy one hour prior** to the earthquake, according to the magnetometer data of Kodiak station located 30 km northwestward from the surface indications of the fault line (along which a shift took place during the earthquake) and 440 km from the epicenter. It should be emphasized that the problem of revealing short-term (days-hours) earthquake precursors is the most acute one.

7. CONCLUSIONS

The picture of the spatial-temporal variations in the *F2* region of the ionosphere prior to the catastrophic earthquake occurred in Alaska on March 28, 1964, has been studied. An analysis of the spatial distribution of the critical frequencies of the ionospheric *F2* layer in the Alaskan region a few hours prior to the earthquake shows that the maximum disturbances of the critical frequency were observed in the vicinity of the epicenter. It has been found that, at least, during a few hours prior to the earthquake, specific regional disturbances appeared in the ionosphere both near the epicenter of the earthquake (~100 km) and at a considerable distance from it (-1000-1500 km) against a quiet background of solar and geophysical activity (during two days prior to the earthquake, the daily mean sunspot number was about 15, and the mean value of the *AE* index was about 30 nT). It has been obtained that, in the vicinity of the earthquake epicenter at Anchorage ground-based ionospheric station, located at a distance of 124 km from the epicenter, the amplitude of the disturbed **daytime values of** *foFl* reaches -25% 4.5 h prior to the main underground shock.

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