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Interpretation of a Statistical Analysis of Variations in the *foF*2 Critical Frequency before Earthquakes Based on Data from Chung-Li Ionospheric Station (Taiwan)

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Abstract—A statistical analysis of variations in the *foF*2 critical frequency before earthquakes has been additionally interpreted based on data from Chung-Li ionospheric station (Taiwan). The interpretation is based on the spatial distribution of earthquakes on Taiwan, depending on a source depth. A complicated shape of the ionospheric precursors of earthquakes is also explained on the basis of a developed physical model.

1. INTRODUCTION

A statistical analysis of the *foF*2 critical frequency variations before earthquakes from Chung-Li (Taiwan) ionospheric station data for the period 1978–1986 has been performed [9]. As a result, the so-called "masks" of precursors were found, which allows us to distinguish them against a background of other variations in the ionosphere caused mainly by solar and geomagnetic activity. The approach assumes that the precursor shapes as the function of the local time and the time before the earthquake should be similar for all earthquakes. It turned out that only deep ($h > 60$ km) earthquakes satisfy the similarity criterion. For smaller earthquakes, the observed chaotic picture does not allow us to construct the "mask" common for all events. As a result, it was concluded that the zone occupied by the anomalous electric field—the source of variations in the ionosphere—increases for deep earthquakes. An additional analysis of the studies of the earthquake preparation zone [1, 2, 5, 12] indicated that this conclusion is not consistent with estimates used in seismology, which makes us to use a new approach in interpreting results of statistical data processing. In a repeated analysis we used data on the distribution of earthquake sources as a function of the depth on Taiwan and in adjacent subduction zones [14]. This analysis made it possible to alternatively interpret results of the statistical data processing proposed in this work.

2. EARTHQUAKE PREPARATION ZONE AND ANOMALOUS ELECTRIC FIELD

The studies of Soviet researchers at the Garm testing range (Tajikistan) in the 1970s, as well as the studies of western scientists, indicated that the changes in the Earth's crust in the form of deformations, variations in seismic waves, emanation of gases from the Earth's crust, and changes in electrical conductivity are observed not only in the earthquake source but also in the zone exceeding the source dimensions by an order of magnitude. This made it possible to develop a dilatation theory—deformation of the Earth's crust, fracturing, and formation of a main fault in the so-called zone of earthquake preparation [6, 11]. The dimensions of this zone were estimated by Dobrovolsky [2], based on calculating the Earth's crust elastic deformation at a level of 10^{-8}, and can be presented in the form

$$\rho = 10^{0.43M}\ \text{km}, \quad (1)$$

where ρ is the radius of the earthquake preparation zone, and M is the magnitude. The radius of the earthquake preparation zone is shown in table.

Magnitude	3	4	5	6	7	8	9
ρ (km)	19.5	52.5	141	380	1022	2754	7413

Calculation results for the Earth's crust mechanical deformation for the case of three-dimensional inclusion with regard to the source depth are given in [1]. In this case the preparation zone is estimated as

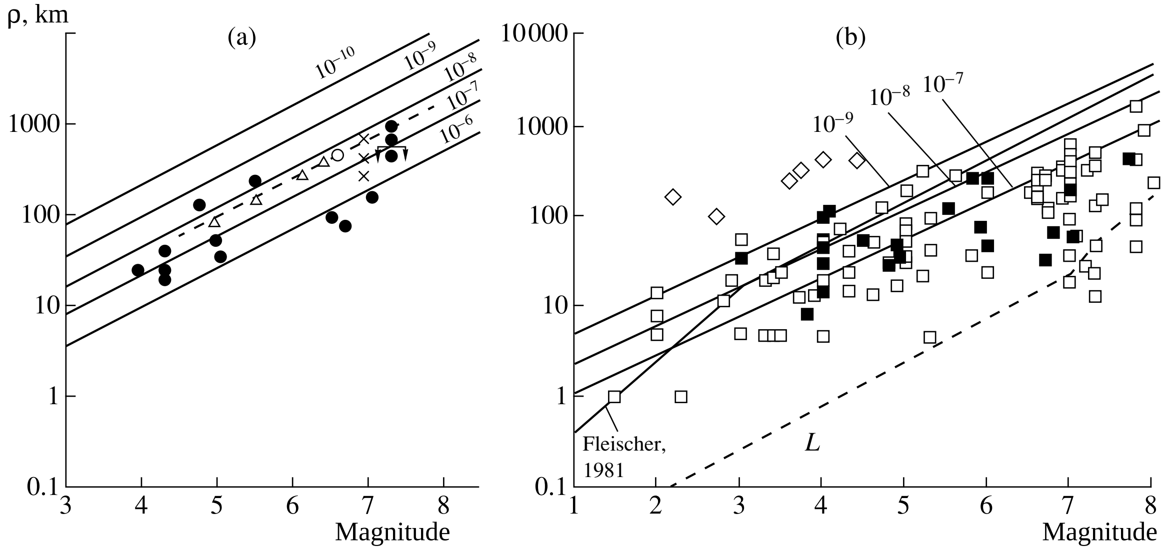

Fig. 1. (a) The distance from the precursor to the epicenter as a function of the earthquake magnitude. Geochemical precursors are denoted by filled circles; the resistance from different sources, by dashes and crosses; telluric currents, by triangles; radon, by arrows; and light effects, by open circles. (b) The distance from the precursor to the epicenter as a function of the earthquake magnitude for geochemical data [12]. Opened and filled squares denote measurements of radon and other gaseous anomalies, respectively. Continuous thin lines show the relation between the deformation radius and magnitude for deformations of 10^{-7} to 10^{-9} in accordance with the empirical equation of Dobrovolsky *et al.* [2]. Thick line represents the empirical dependence derived by Fleischer (1981) as a result of calibrating the maximal distance between the measured anomaly and epicenter for a given magnitude on the basis of the shear dislocations law for earthquakes. The dashed line shows the typical size of the rupture zone of an active fault as a function of magnitude in accordance with the empirical equation of Aki and Richards [15].

$$a = 10^{0.414M - 1.696}\ \text{km}, \qquad (2)$$

where a is the deformation zone radius at a level of 10^{-8} with regard to the source location within the Earth's crust.

Although a dilatation theory is valid only for shallow earthquakes and recent prognostic papers are based on the statistical processing of seismic data, a theory of chaos, and critical states of self-organized systems [5], dimensions of the preparation zone are estimated as before.

The validity of using the Dobrovolsky's formula for evaluating ionospheric effects used in [7, 8] should be discussed. Radon, the emanation of which from the Earth's crust is observed in earthquake preparation zones, is used as an ionization source in the mechanism of generation of an anomalous electric field. Consequently, the answer should be looked for in the literature describing geochemical effects before earthquakes. In a critical review [12], listing more than 150 publications of different authors on measurements of geochemical earthquake precursors, Toutain and Baurbon estimated the zone where geochemical precursors (including radon) were observed as a function of magnitude (Fig. 1b) and concluded that the zone of geochemical precursors is completely identical to the zone calculated by Dobrovolsky (Fig. 1a). Moreover, Fleischer, based on an analysis of geochemical data, obtained his own dependence of the zone with observed geochemical precursors on magnitude (Fig. 1b), which

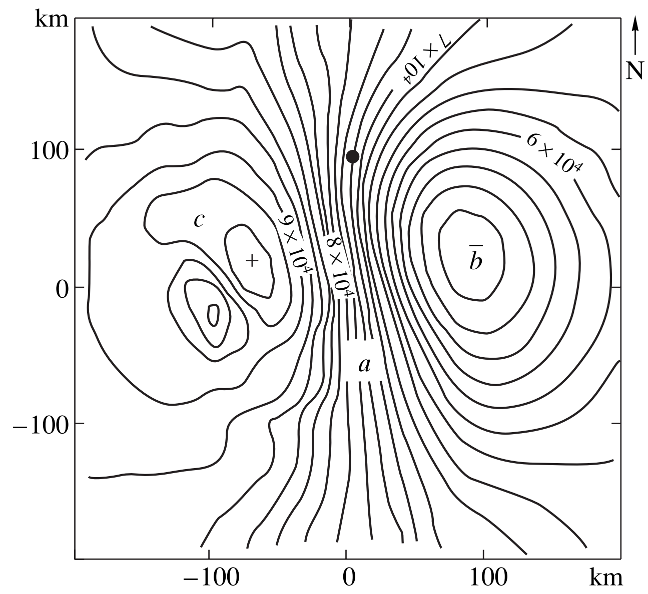

Fig. 2. Dependence of the critical frequency deviation sign before an earthquake on the relative position of the ionosonde and the epicenter of an impending earthquake at an invariable distribution of the deviation in the $F2$ layer: (*a*) the deviation is zero, the ionosonde "does not see" an anomaly in the ionosphere, and the epicenter is located northward of the ionosonde; (*b*) the deviation is negative, and the epicenter is located northwest of the ionosonde; (*c*) the deviation is positive, and the epicenter is located northeast of the ionosonde.

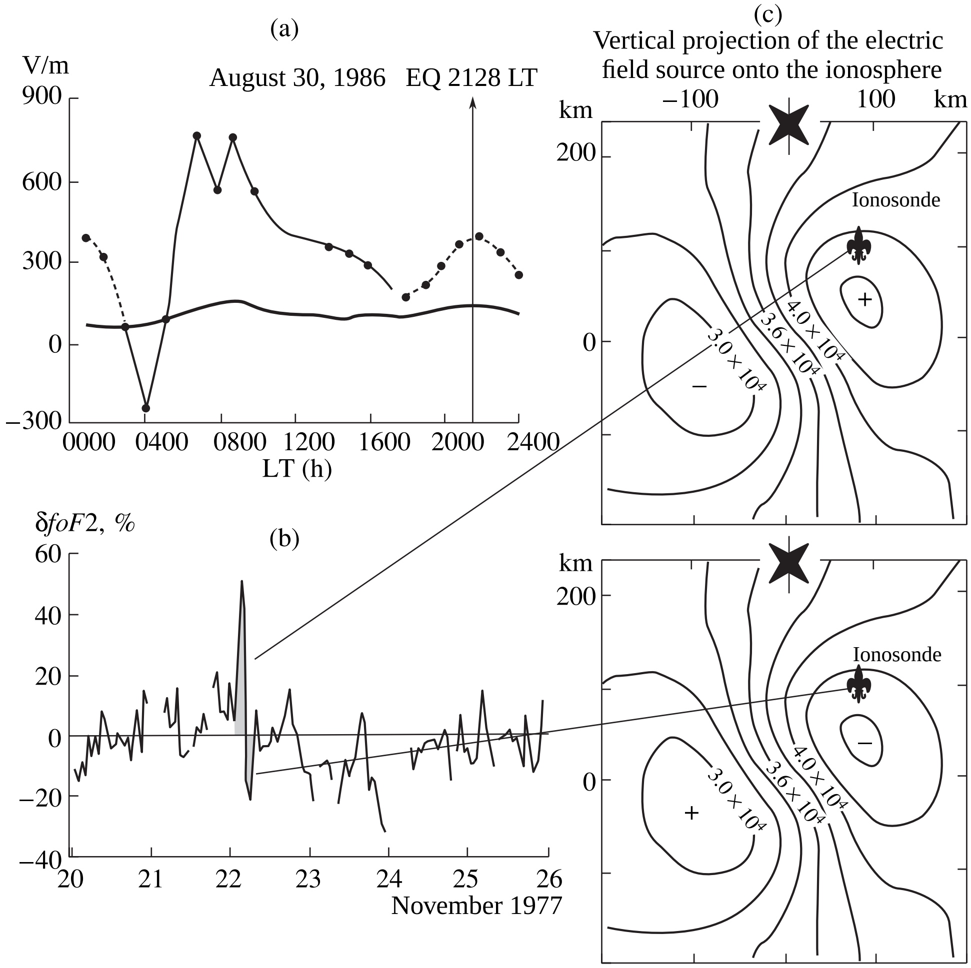

Fig. 3. Dependence of the critical frequency deviation sign before an earthquake on the direction of an anomalous electric field: (a) an example of the variation in an anomalous electric field before an earthquake in the Carpathians on August 30, 1986 ($M = 7.0$) with the field sign inversion; (b) an example of the ionospheric precursor (the deviation of the critical frequency *foF*2, %) before an earthquake in Caucette (Argentine) on November 23, 1997 ($M = 7.8$), recorded at Tucuman ionospheric station. Note that in cases (a) and (b) the distance from the epicenter to the ground-based station was about the same (700–800 km), which corresponds to the dimensions of the earthquake preparation zone for $M \geq 7$; (c) the model presentation of the distribution of the critical frequency deviation in the ionosphere at 500 km altitude and of the correspondence of the deviation sign to that measured experimentally.

almost completely coincides with the curve obtained by Dobrovolsky. Thus, we can state that the zone occupied by the anomalous electric field, computed in the model [8], can be estimated from formula (1). Hence, it becomes clear that the appearance of the magnitude threshold ($M \sim 5$) can be used to detect ionospheric earthquake precursors. According to the calculations [8], an anomalous electric field can effectively penetrate into the ionosphere, if the minimal size of the zone with this field is 200 km, which corresponds to a magnitude of $M = 4.65$ according to (1). Since this is a minimal estimate, a threshold of $M \sim 5$ seems quite reasonable and corresponds to experimental observations.

An analysis of estimates (1) and (2) shows that the conclusion [7] that the radius of the earthquake preparation zone for deep events is larger than for shallow ones is groundless. This makes it necessary to search another explanation for the result obtained in the cited work, which will be done below.

3. RELATIVE POSITION OF EPICENTER AND IONOSONDE AND THE SIGN OF DEVIATION OF IONOSPHERIC PRECURSOR

The calculations performed according to the model [8] show that the structure of the electron concentration variations in the ionospheric *F*2 layer is complicated (two-pole) and is displaced southward (in the Northern Hemisphere) relative to the vertical projection of the source of an anomalous electric field (epicenter) onto the ionosphere. The ground-based ionosonde will receive vertical ionospheric reflections, and the ionosonde data will differ for the same precursor type, depending on its position relative to a future epicenter. This is illustrated in Fig. 2 for four relative positions of

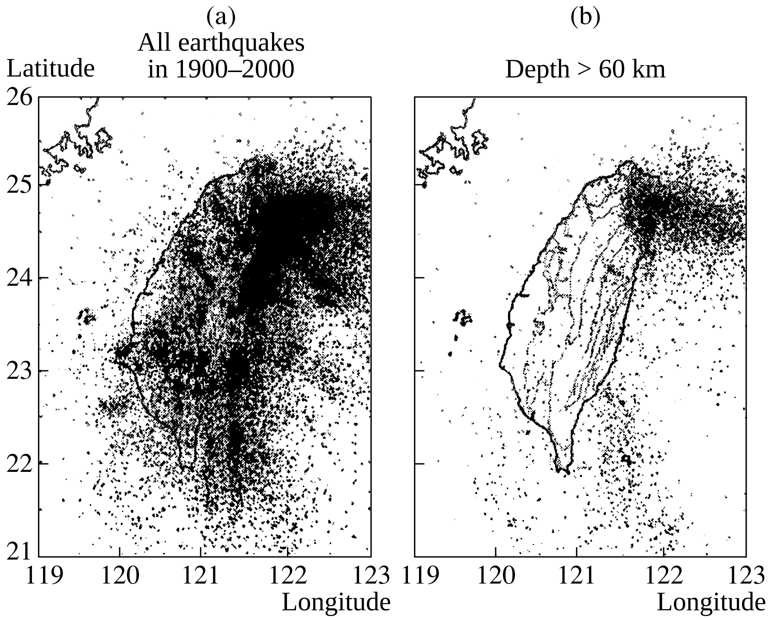

Fig. 4. The spatial distribution of the earthquake epicenters on Taiwan and in its vicinity in 1900–2000: (a) for all earthquakes independently of a focus depth, and (b) for earthquakes with a depth of $h > 60$ km [14].

the epicenter and ionosonde and for the same ionospheric distribution. In the case *a* (the ionosonde is located exactly south of the epicenter), the deviation will be zero, and the ionosonde will not detect the precursor, whereas the deviation will be negative in the case *b* (the ionosonde is located southeast of the epicenter) and positive in the case *c* (the ionosonde is located southwest of the epicenter).

From this consideration we can conclude that the precursor's shape for different earthquakes will be similar only in the case when epicenters of these earthquakes are in the same zone relative to the position of the observing ionosonde.

4. SHAPE OF IONOSPHERIC PRECURSOR AND VARIATIONS IN ANOMALOUS ELECTRIC FIELD

The second factor, affecting the shape of a detected ionospheric precursor, is the direction of an anomalous electric field. As experiments show [3, 13, 16], an anomalous electric field detected prior to an earthquake can change the sign. As a result, the distribution of electron density deviation in the ionosphere will also change with changing signs of the poles of the two-pole structure detected in the ionosphere (Fig. 3). In addition, variations in the amplitude of an anomalous electric field will also cause changes of the size of disturbed ionospheric regions, which will result in the variation in the amplitude and, under a certain relative position of ionosonde and epicenter, in the change of the variation sign. The size of disturbed ionospheric regions will also change also depending on the earthquake magnitude, as follows from Eq. (1). Correspondingly, a signal recorded by an ionosonde will also change.

Moreover, we should not forget about the ionosphere itself. As was shown in [4], the efficiency of the anomalous electric field penetration into the ionosphere at night is higher than in daytime. Pulinets *et al.*, [10] indicated that the shape and amplitude of an ionospheric precursor depend on local time, which can be explained, for example, by diurnal regular variations in plasmaspheric fluxes of atomic oxygen ions. We should not forget that electric fields of a different nature, for example, the zonal electric field at the magnetic equator in the afternoon, responsible for the formation of the equatorial anomaly, exist in the ionosphere. All these factors will affect variations caused by a seismic electric field, making the ionosonde-detected pattern even more complicated.

From the above discussion we can draw the following conclusions:

(1) A complicated shape of ionospheric earthquake precursors, derived from ground-based ionosonde observations, can be explained by the variation in the following factors: relative position of an ionosonde and a future earthquake epicenter, amplitude and sign of an anomalous electric field, magnitude and other parameters (depth, focus mechanism, etc.) of an impending earthquake, local time, and presence of an electric field of a different (independent of earthquake) origin in the ionosphere.

(2) A similarity between the shapes of ionospheric precursors of different earthquakes, detected by a ground-based ionosonde, can be the same or rather close only in the cases when epicenters of these earth-

quakes are in the region of location of an ionosonde. Note that in this sense satellite observations are more impartial since they are independent of this factor.

5. INTERPRETATION OF STATISTICAL PROCESSING OF DATA FROM THE CHUNG-LI IONOSONDE, TAIWAN

Consider now results of the statistical processing of Chung-Li (Taiwan) ionosonde data on recording ionospheric earthquake precursors for 1977–1986. The main result of this work is the conclusion that the two-dimensional pattern (the earthquake "mask") is similar only for earthquakes deeper than 60 km. For shallow-focus earthquakes, the observed picture is chaotic. As was shown above, this result cannot be explained by a difference in the dimensions of the earthquake preparation zone for deep and shallow earthquakes. At the same time, the attention should be drawn to the spatial distribution of earthquakes in the Taiwan region as a function of depth. On the International Seminar on Earthquake Precursors (project ISTEP, Integrated Search for Taiwan Earthquake Precursors, June 5–6, 2002, Chung-Li, Taiwan), Wang and Shin [14] presented data on such a distribution, part of which are shown in Fig. 4. It would be appropriate here to stop the discussion since the Fig. 4 even should not be discussed and is evident. It is absolutely evident that this figure confirms the conclusion made in Section 2 that the shape of ionospheric precursors, detected by a ground-based ionosonde, will be similar only in the case when locations of earthquake epicenters are close to each other and are approximately in the region of location of a ground-based ionosonde. Precisely earthquakes, the sources of which are deeper than 60 km, are concentrated in the subduction zone located northeast of Taiwan and are rather close to the ionosonde, also located in the northern part of the island. This cluster of earthquakes makes the main contribution to the obtained precursor's "mask". Figure 4a indicates that other earthquakes with a source depth of less than 60 km are scanty and are distributed over the entire island. Their distances from the ionosonde are larger, and their contribution to the data processing is insignificant.

The second conclusion made in [7] seems to be correct: the division of precursors into two groups is related to the positive and negative directions of an anomalous electric field.

6. CONCLUSIONS

A performed analysis of the statistical processing of the long series of measurements (1978–1986) at Chung-Li ionospheric station (Taiwan) made it possible to derive the dependence of the shape of variations in the deviation of the critical frequency from the undisturbed value (interpreted as a short-term earthquake precursor) on the relative position of earthquake epicenters and ionosonde. Possible dependences on other geophysical factors were also discussed. These results should be taken into account when developing techniques for statistical processing of ionospheric data and when applying the pattern recognition method to identification of earthquake precursors.

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