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Regularities in the Manifestation of Earthquake Precursors in the Ionosphere and Near-Surface Atmospheric Electric Fields in Kamchatka

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Abstract—The data of hourly measurements of ionospheric parameters in Petropavlovsk–Kamchatsk are analyzed for the period 1998–2002. In the vertical component of near-surface atmospheric quasistatic electric field *Ez*, earthquake precursors in the form of anomalous negative bays have been found earlier. In some cases, anomalously high sporadic layer *Es*, interpreted as an ionospheric precursor of an earthquake, was observed simultaneously with anomalous negative bays in *Ez*. All these cases were correlated with earthquakes of different magnitudes which occurred with a significant time delay (more than five days) after the precursor appearance. Based on the whole data set (including those for simultaneously measured *Es* and *Ez*), empirical dependences linking the prediction time of a precursor, earthquake magnitudes, and the distance from the observation point to the epicenter, are presented. It is shown that these dependences are close to those obtained earlier for long-term earthquake precursors in near-surface geophysical fields of the same seismoactive region. Estimates of the prediction time for earthquake precursors on the boundaries of preparation zones are presented.

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1. INTRODUCTION

Many earthquake precursors have been found by now; these precursors are seen as significant variations in parameters of different geophysical fields within the lithosphere, lower atmosphere, and ionosphere of the Earth (Zubkov and Migunov, 1975; Sidorin, 1979, 1992; Zubkov, 1983, 1987; Liperovskly et al., 1992; Gufel'd and Gusev, 1998; Korsunova and Khegai, 2006; Ismagilov et al., 2006; Kopylova and Serafimova, 2010). The world data on earthquake precursors in different near-surface geophysical fields analyzed has allowed researchers to conclude that almost all of these precursors reveal long- (from years to tens of years for $M \geq 6$), medium- (from weeks to months), and short-term (from hours to days) anomalous variations that reflect different rubies of seismic event preparation (Zubkov, 1987). It has also been shown that the prediction time of earthquake moments by long- and medium-term precursors in the epicentral zone is strongly correlated with the earthquake magnitude and grows with increasing magnitude. However, as the distance to an epicenter increases, the prediction period of the appearance of precursors depends on both the energy of the upcoming event and the distance between the observation point and the future event's epicenter. For example, it was found in (Sidorin, 1979) that, when considering the distance between an observation point and an earthquake epicenter, all precursors can be subdivided into two large groups: long- and short-term. It was revealed that some precursors that appear immediately prior to an earthquake are in fact long-term ones, but they manifest themselves at a significant distance from the epicenter of the respective upcoming event. These groups are characterized by certain different dependences written as $\log(\Delta T \times R) = aM + b$, where M is the earthquake magnitude; R is the distance between the epicenter and an observation point; and ΔT is the time period elapsed since the appearance of a precursor until the earthquake occurrence (prediction time). There are other dependences of this kind (Gufel'd and Gusev, 1998), but most of them are derived from ground-based observations. Substantial advances in studying the regularities in the appearance of earthquake precursors in the lower (including the near-surface layer) and upper atmosphere have been made in the last decade (Hao et al., 2000; Korsunova and Khegai, 2005, 2010; Liu et al., 2006; Korsunova et al., 2010b). In these publications, empirical dependences of both prediction times of earthquake precursors and precursor detection probabilities on the magnitudes of the upcoming earthquakes and distances between their epicenters and observation points were obtained. Dependences of the precursor appearance time on the magnitude and epicentral distance were obtained from both ionospheric measurements and observations of atmospheric electric fields (Korsunova et al., 2010b). Based on literature data, the prediction time of a precursor appearance is also dependent on the hypocenter depth of a preparing earthquake (Mikhailov, 2007; Bakhmutov et al., 2007; Xia et al., 2011).

An analysis of multiannual ionospheric observations in seismoactive zones has allowed us to distinguish the anomalies in ionospheric parameters, corresponding to different stages of earthquake preparation and being identified as long- and medium-term earthquake precursors (Korsunova and Khegai, 2006; Perrone et al., 2010; Korsunova et al., 2010b). It has been found that regularities in manifestations of anomalies in the ionosphere correspond to the results of ground-based observations. Undoubtedly, empirical dependences that link the prediction time of the appearance of an earthquake precursor with the event's magnitude and epicentral distance to the observation point are of great interest, but all of them were obtained in epignosis. It is natural to question whether earthquake precursors are followed by earthquakes in real time. Indeed, in some cases, this is not true (Smirnov, 2005; Perrone et al., 2010). Therefore, it is important to distinguish real precursors that are followed by earthquakes from false ones (i.e., illogical anomalies that do not indicate upcoming earthquakes). We have earlier brought a few examples that, if measurements were carried out in the same point and precursors appeared in the atmospheric quasistatic electric field and in the ionosphere, they were usually followed by earthquakes (Korsunova et al., 2010b). If this conclusion is verified for other earthquakes, then real precursors can be distinguished from simultaneous measurements of ionospheric parameters and the *Ez* component of the near-surface quasistatic electric field at one point.

For this purpose, we considered the measurement results of the *Ez* component of the near-surface atmospheric quasistatic electric field, obtained by one of the authors, and of ionospheric parameters in the settlement of Papatunka, Kamchatka oblast, in the period 1998–2002. Hourly data of ionospheric observations for the studied period were taken from the NOAA National Geophysical Data Center (NGDC), United States.

2. STUDY METHOD AND DATA ANALYSIS

In (Smirnov, 2005), there were 103 negative bays in the *Ez* component of the near-surface atmospheric quasistatic electric field, which had been distinguished from observations of the gradient of electric field potential under "good weather" conditions and which were usually referred to earthquake precursors. However, only 37% of these bays were followed by earthquakes of $K = 11–15$ ($M = 4.7–6.7$) in energy class at epicentral distances $R = 100–1000$ km within the following 24-h period. These cases likely refer to short-term earthquake precursors. A certain part of the remaining negative anomalies of the *Ez* component might belong to medium- and long-term precursors, as it was revealed in China (Hao et al., 2000). If this suggestion is true, then, according to (Korsunova et al., 2010b), in addition to precursors in the *Ez* layer, there may be ionospheric precursors (in particular, in the sporadic *Es* layer) on the same days. In order to verify this, we processed the data of hourly ionospheric observations made at the same point for the same years and months when earthquake precursors were observed in the near-surface electric fields (Smirnov, 2005).

Due to the fact that specific ionospheric anomalies that are exclusively related to earthquake preparation (not to other geophysical phenomena, such as magnetic storms) have not been found yet, it is believed that statistically significant variations in any ionospheric parameter (critical frequency of the *F*2 regular layer (*foF*2), limited frequency of reflection from sporadic layer *E* (*fEs*), screening frequency (*fbEs*), and others) can be a precursor (Liperovskly et al., 1992; Gufel'd and Gusev, 1998; Ondoh, 2003; Pulinets and Boyarchuk, 2004; Hobara and Parrot, 2005; Liu et al., 2006; Oyama et al., 2011). In the previous publications (Korsunova and Khegai, 2006, 2008), we suggested a method to distinguish an earthquake's ionospheric precursor based on a certain set of morphologic signs revealed from long-term observations of the ionosphere prior to earthquakes of different energy classes in various seismoactive regions instead of relying on only one parameter. According to this method, there are the following typical features of ionospheric precursors of earthquakes:

—appearance of anomalously high sporadic layer *E* (*Es*) that exceeds the background values of virtual height (*h*'*Es*) under quiet geophysical conditions for a concrete time of the day by at least 10 km during a period of 1–3 h;

—an increase in *Es* frequencies by at least 20% accompanied by growth in *foF*2 during the same period within a day (±12 h) relative to the moment of the appearance of anomalously high *Es*.

This method was tested for crustal earthquakes (hypocenter depth of no more than 60 km) with the use of data of vertical ionospheric sounding in seismoactive regions, such as Japan, Kamchatka, Cis-Baikalia, and Italy (Korsunova and Khegai, 2008; Korsunova et al., 2010a, 2010b; Perrone et al., 2010), and earthquake precursors of different prediction time (ΔT) were revealed. At this point, we should note that the application field of the suggested method is naturally confined to latitudes where midlatitude sporadic layer *E*, which follows well-known day and seasonal regularities, is observed (Chavdarov et al., 1975). Since anomalous changes in *Es* parameters are the basis of our method, a comparative analysis of supposed earthquake precursors observed in *Es* and *Ez* parameters is only possible for months when the probability of the sporadic *E* layer appearance is at least 50%. For Petropavlovsk–Kamchatsk (the coordinates of the ionospheric probe are $\varphi = 53.02°$ N and $\lambda = 158.65°$ E), these are mainly summer months. Thus, we processed the data of ionospheric observations for August 1998, June–August 1999, July 2000, May–June and August–September 2001, and April–May 2002. To find ionospheric precursors, we performed the following routine tasks:

—calculated the deviations of the current values of the effective *Es* height ($\Delta h'Es$), screening frequencies ($\Delta fbEs$), and the critical frequencies of the *F*2 layer ($\Delta foF2$) from the average values of these parameters based on geomagnetically quiet days ($Ap \le 10$–15 nT);

—determined the days when the deviations of all three parameters corresponded to the criteria for choosing an ionospheric precursor, i.e., $\Delta h'Es \ge 10$ km, $\Delta fbEs/(fbEs)_{av} \ge 20\%$, and $\Delta foF2/(foF2)_{av} \ge 10\%$ for the time period $\tau = 1$–3 h.

For all above-mentioned periods, anomalies in *Es*, corresponding to the choice criteria of an ionospheric earthquake precursor, were detected in 19 cases. In 13 cases, the distinguished precursors were followed by earthquakes of $M = 5.0$–6.0 which occurred with different delays (ΔT) and at different distances (100–400 km) from the observation point.

In six cases, the *Es* anomalies observed under quiet heliogeomagnetic conditions were not followed by earthquakes of the mentioned magnitude, hence "false alarms" constituted 32%. All real ionospheric precursors followed by earthquakes are given in Table 1, which also contains the distances (R) between epicenters and the observation point, calculated by the big circle arc, taking into account the *Es* altitude. Note that ionospheric information is gathered with a probe from a relatively large domain of at least 50 km in size, but, for more certainty in further calculations, we use these computed distances. In 7 out of the 13 revealed precursors in *Es*, precursors in the electric field were detected on the same days (in Table 1, these cases are marked with asterisks). The absence of precursors in *Ez* in the rest of the cases can be related to the impossibility of its reliable identification based on weather conditions.

In the same months, anomalous negative bays were revealed in the *Ez* component of the electric field, and they were not accompanied by either *Es* anomalies or earthquakes (36%). They were observed both on the days of magnetic storms and on quiet days but belong to "false precursors," because they cannot be correlated with any earthquakes. Thus, the number of "false alarms" in observations of *Ez* anomalies is nearly the same as for ionospheric observations. However, all *Ez* precursors were followed by earthquakes and *Es* precursors were manifested for these events as well. Therefore, under "good weather" conditions, real precursors in *Ez* can be distinguished from false ones only if data from simultaneous ionospheric measurements are available. Real precursors in *Es* and *Ez* manifest themselves on the same days, so they have equal prediction times for respective earthquakes (see Table 1).

For all distinguished ionospheric precursors of earthquakes, one can see that the prediction time of an earthquake by a precursor depends on the magnitude of that earthquake (M) and the epicentral distance to the observation point (R). The larger the M value, the earlier a precursor appears for earthquakes with equal R; i.e., prediction time ΔT is longer (see Table 1, nos. 5, 6). As R increases for equal M, the prediction time of a precursor decreases (see Table 1, nos. 2, 4, 9, 10). Such behavior is typical of medium- and long-term precursors and indicates the propagation of a disturbance from an epicenter to the boundaries of the earthquake preparation zone (Gufel'd and Gusev, 1998).

In the equinox months and winter, the sporadic *E* layer rarely appears at a latitude of Petropavlovsk–Kamchatsk, so reliable information on precursors in *Es* cannot be acquired for these periods; real precursors in *Ez* for these months were distinguished from the found anomalies based on the above-mentioned dependence of the precursor appearance time on the magnitude and epicentral distance. Eleven probable precursors in *Ez*, followed by $M \ge 5.0$ earthquakes several days or weeks later, were distinguished (Table 1, nos. 14–16, 18–20, 23, 25–27, 30).

DISCUSSION

The figure presents the changes in the prediction time for earthquakes by all distinguished real precursors in *Es* (diamonds) and *Ez* (points), depending on the magnitude of the following earthquakes. Horizontal arrows indicate precursors of the same events obtained through simultaneous measurements of *Es* and *Ez* parameters. For two groups of precursors in *Es* and *Ez*, the linear regression lines (solid line is *Es*, pointed line is *Ez*), obtained by the least squares method

$$\log(\Delta T \times \mathrm{R})_{Es} = 0.85M - 1.23, \quad (1)$$

$$\log(\Delta T \times R)_{Ez} = 0.9M - 1.5 \quad (2)$$

are given with the respective standard deviations (dashed line). The correlation factors for a 5% significance level by Student's test for the chosen cases are $\rho_{Es} = 0.98$ with the confidence interval (0.96; 0.99) and $\rho_{Ez} = 0.97$ with the confidence interval (0.96; 0.99). The figure also illustrates the dependence of the prediction time by a long-term precursor on magnitude (dash–dot line), obtained in (Sidorin, 1992) for different ground-based observations carried out in the same seismoactive region but in different years (geo-

Table 1. Characteristics of earthquakes and their probable long-term precursors

No.	Earthquake date	M	R, km	Precursor date	ΔT, days
Anomalies in the sporadic E layer (Es)					
1*	30.08.1998	5.6	260	16.08.1998	14.5
2*	13.07.1999	5.0	180	08.07.1999	5.8
3*	06.08.1999	5.9	370	21.07.1999	15.2
4*	06.09.1999	5.0	120	28.08.1999	9.3
5*	18.09.1999	6.0	200	10.08.1999	39.9
6	12.05.2000	5.2	210	07.05.2000	5.5
7	03.06.2000	5.5	130	10.05.2000	24.0
8	08.06.2000	5.1	130	29.05.2000	9.8
9	01.09.2001	5.3	140	14.08.2001	17.0
10*	08.10.2001	5.3	160	26.09.2001	11.6
11*	10.10.2001	5.4	170	24.09.2001	15.6
12	08.05.2002	5.9	200	06.04.2002	32.0
13	29.05.2002	5.1	210	22.05.2002	7.0
Anomalies in the vertical component of the near-surface electric field (Ez)					
14	09.02.1997	5.9	350	19.01.1997	21.1
15	06.12.1997	6.1	270	02.11.1997	34.0
16	07.12.1997	6.2	360	27.10.1997	40.4
17*	30.08.1998	5.6	250	16.08.1998	14.5
18	11.01.1999	5.6	130	08.12.1998	33.8
19	08.03.1999	5.8	120	02.01.1999	64.0
20	07.07.1999	6.1	460	23.06.1999	14.5
21*	13.07.1999	5.0	180	08.07.1999	5.8
22*	06.08.1999	5.9	360	21.07.1999	15.2
23*	06.09.1999	5.0	110	28.08.1999	9.3
24*	18.09.1999	6.0	200	10.08.1999	39.9
25	31.12.1999	5.0	120	22.12.1999	9.3
26	27.08.2000	5.1	40	24.07.2000	33.7
27	17.09.2001	5.3	100	31.08.2001	17.0
28*	08.10.2001	5.3	150	26.09.2001	11.6
29*	10.10.2001	5.4	170	24.09.2001	15.6
30	28.01.2002	6.1	440	01.01.2002	27.5
31	08.05.2002	5.5	150	22.04.2002	15.4

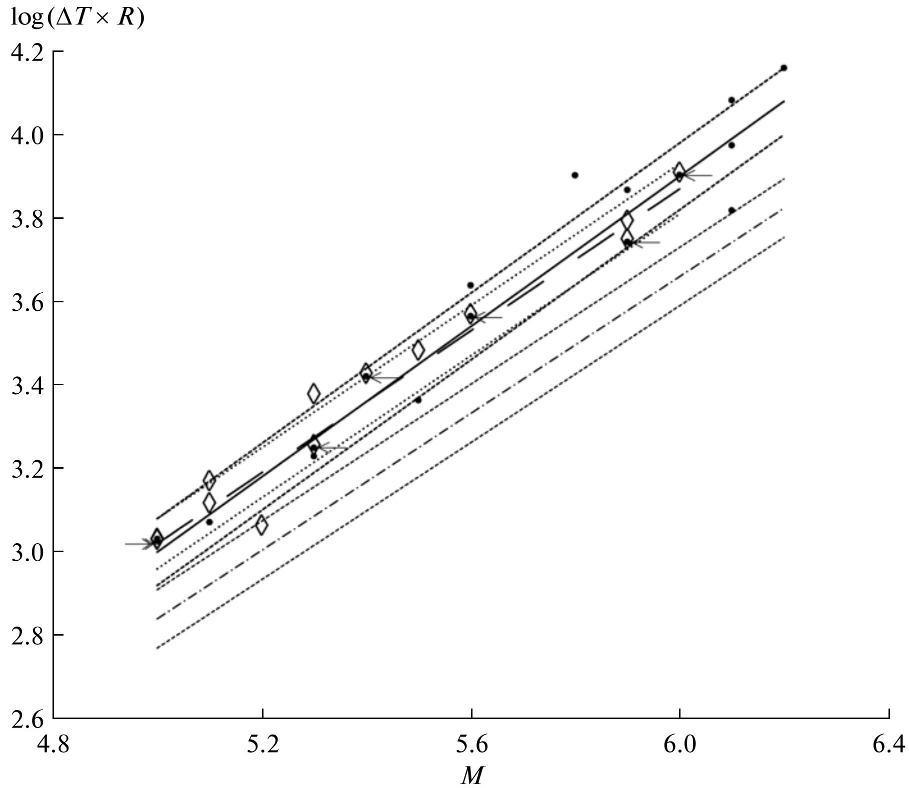
detic measurements, electrotelluric fields, ground water level, and the Earth's surface tilts):

$$\log(\Delta T \times R)_{\text{Sidorin}} = 0.82M - 1.26. \quad (3)$$

All characteristics of the presented dependences $\log(\Delta T \times R) = aM - b$ are given in Table 2.

It can be seen that, despite a limited number of chosen cases, the computed correlation factors indicate quite a high accuracy of the obtained dependences of the prediction time on magnitude at certain epicentral distances.

It follows from the figure that the dependences for earthquake precursors in electric fields and in the ionosphere nearly coincide. The different coefficients in formulas (1) and (2) are likely related to a certain variety of earthquakes and not only to different numbers of earthquakes used for Es and Ez. The regression line plotted from ground-based observational data (Sidorin, 1992) lies below these dependences. This may mean that precursors in the near-surface and upper atmosphere (ionosphere) appear earlier than on the ground level for the same M and R values.



Empirical dependences of the prediction time of earthquakes (ΔT) on the magnitude (M) and the epicentral distance (R) to an observation point for anomalies in *Es* (diamonds, solid regression line) and *Ez* (points, dashed regression line) and based on the data from different ground-based observations generalized in (Sidorin, 1992) (dash–dot line). The respective standard deviations of the regression lines are shown with dashed lines. Horizontal arrows denote precursors of the same events obtained through simultaneous observations of the *Es* and *Ez* parameters.

The numerical coefficients in the given formulas, especially in (1) and (3), are close to each other, indicating a higher accuracy of identification for ionospheric precursors of earthquakes based on the suggested method. Dependence (3) was obtained in (Sidorin, 1992) exactly for long-term precursors; therefore, precursors distinguished in *Ez* and *Es* can be referred to the group of long-term ones in the near-surface and upper atmosphere, respectively. Moreover, formulas (1)–(3) have a clearly defined physical sense. Firstly, they show the direction of seismic disturbance propagation. Indeed, every point on the regression line satisfies the coordinates $\{M, \log(\Delta T \times R)\}$. For a concrete magnitude, $\log(\Delta T \times R) = \text{const}$ if one neglects the error in the M coordinate determination ($S = 0.06–0.08$), as is illustrated by the figure.

This means the following: for two different epicentral distances, the correlation $\log(\Delta T_1 \times R_1) = \log(\Delta T_2 \times R_2)$ is satisfied; hence $\Delta T_1 \times R_1 = \Delta T_2 \times R_2$ and $\Delta T_1/\Delta T_2 = R_2/R_1$. At $R_2 > R_1$, a precursor will appear earlier at a station located closer to the epicenter (ΔT_1) and the time (R_2) will be proportionate in comparison to the distance to the second station (R_1). This peculiarity indicates the propagation of a seismic disturbance from an epicenter to the boundaries of the earthquake preparation zone.

Table 2. Characteristics of linear regression for different earthquake precursors

Parameters of	a	b	S_a	S_b	S	ρ	n
Ez	0.90	1.5	0.05	0.3	0.08	0.98	18
Es	0.85	1.23	0.05	0.26	0.06	0.98	13
[Sidorin, 1992]	0.82	1.26	0.05	0.32	0.42	0.93	43

Note: S_a and S_b are the standard deviations of the a and b regression coefficients, S is the standard deviation error, ρ is the correlation factor of the M and $\log(\Delta T \times R)$ values, and n is the number of considered cases.

Second, dependences (1)–(3) for long-term precursors allow one to determine the prediction time for an earthquake on the boundary of the preparation zone, the radius of which is found from the Dobrovolsky formula (Dobrovolsk et al., 1980): $\log(r) = 0.43\,M$ (in kilometers). In this case, $R = r$; $\log(\Delta T \times r) = aM + b$; and

$$\log(\Delta T) = (a - 0.43)M + b. \quad (4)$$

Since atmospheric precursors detect the boundary of an earthquake zone, one can determine the prediction time (ΔT) for an earthquake from different precursors on the basis of Eqs. (1)–(3), taking into account the standard deviations of the a and b coefficients (Table 2). Calculations show that, for $M = 5.0$ and $r = 150$ km, the prediction time on the boundary of an earthquake preparation zone will be 7.25–7.6 (ΔT precursors) and 6.9–7.25 (Es precursors) days, while 4–5.5 days will be required for precursors on the ground level. In the case of $M = 6.0$ and $r = 380$ km, the prediction times will be $\Delta T_{Es} = 18$–21 days, $\Delta T_{Ez} =$ 19–23 days, and $\Delta T_{\mathrm{Sidorin}}$ = 11.5–12.5 days. This means the following:

—in Es and Ez, precursors for the same earthquakes appear nearly simultaneously for $M \leq 6$;

—on the boundary of an earthquake preparation zone, precursors appear depending on the magnitude (the larger the magnitude, the earlier a precursor manifests itself);

—in the near-surface and upper atmosphere (ionosphere), the prediction time of a precursor is longer than on the ground level, independently of the magnitude.

The above-given calculations are made under the assumption that the boundaries of earthquake preparation zones for both ground-level and atmospheric precursors coincide and are determined by the Dobrovolsky formula (Dobrovolsky et al., 1980). However, some publications reported that ionospheric precursors were recorded at distances exceeding the size of the earthquake preparation zone, calculated by the Dobrovolsky formula, by ~100–150 km even for $M = 4$ (Silina et al., 2010). Additionally, precursors of different physical nature manifest themselves at the ground level at different times (Sidorin, 1992). In (Kopylova and Serafimova, 2010), this point was explained by different scales of the stress-strain state of the upper crustal layer. For example, based on measurements of the deformation characteristics of the Earth's crust, the extent of the earthquake preparation zone, determined for 43 precursors, is described by the dependence $\log(L_{\mathrm{r}}) = 0.48M$ (Sidorin, 1992). For $M = 5.0$, $L_{\mathrm{r}} = 250$ km which exceeds the estimate by the Dobrovolsky formula by 100 km but fits the manifestation zone of ionospheric precursors from (Silina et al., 2010).

Using logarithmic dependence (3), one can calculate the propagation rate of the seismic velocity in the near-surface crustal layer from a certain point with epicentral distance R to the boundary of earthquake preparation zone r by the simple formula $V = (r - R)/(\Delta T_R - \Delta T_r)$. For these two considered distances, we have $\log(\Delta T_R \times R) = \log(\Delta T_r \times r) = 0.82M - 1.26 = \log(C)$. Hence, $\Delta T_R = C/R$ and $\Delta T_r = C/r$. For $M = 6.0$, the radius of the earthquake preparation zone $r = 380$ km; a propagating seismic disturbance from an observation point with $R = 100$ km to the boundary of an earthquake preparation zone produces $V_{M = 6.0} \approx 0.35$ km/h. Thus, the obtained logarithmic dependences characterize the average expansion rate of an earthquake preparation zone, depending on the earthquake energy (magnitude).

4. CONCLUSIONS

The conducted study of the effects in the ionosphere and near-surface quasistatic electric field, preceding strong ($5.0 \leq M \leq 6.2$) earthquakes, based on measurements in Kamchatka allows us to make the following conclusions:

1. Real earthquake precursors are observed nearly simultaneously in the sporadic E layer and in the vertical component of the near-surface electric field when measurements are conducted at the same point.

2. The logarithmic dependences that link the earthquake magnitude, prediction time of an earthquake, and the distance between the observation point and epicenter for both the ionosphere and near-surface quasistatic electric field correspond to analogous dependences for long-term earthquake precursors obtained from measurements of different geophysical parameters in the same seismoactive zone.

3. Atmospheric earthquake precursors in the Kamchatka seismoactive zone are the earliest prediction of a probable seismic hazard.

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REFERENCES

Bakhmutov, V.G., Sedova, F.I., and Mozgovaya, T.A., Geomagnetic Disturbance and Earthquakes in the Vranch Zone, *Fiz. Zemli*, 2007, no. 11, pp. 30–36.

Chavdarov, S.S., Chasovitin, Yu.K., Chernysheva, S.N., and Sheftel', V.N., *Sredneshirotnyi sporadicheskii sloi E ionosfery* (Midlatitude Sporadic Ionospheric *E* Layer), Moscow: Nauka, 1975.

Dobrovol'skii, I.A., Zubkov, S.I., and Myachkin, V.I., On the Estimation of Dimensions of the Zone where Earthquake Precursors are Registered, in *Modelirovanie predvestnikov zemletryasenii* (Modeling Earthquake Precursors), Moscow: Nauka, 1980, pp. 7–14.

Gufel'd, I.L. and Gusev, G.A., Present-Day State of Earthquake Predictions (Is There Any Deadlock Recovery?), in *Kratkosrochnyi prognoz katastroficheskikh zemletryasenii s pomoshch'yu radiofizicheskikh nazemno-kosmicheskikh metodov* (Short-Term Prediction of Catastrophic Earthquakes Using Ground–Space Methods), Strakhov, V.N. and Liperovskii, V.A., Eds., Moscow: OIFZ RAN, 1998, pp. 7–25.

Hao, J., Tang, T., and Li, D., Progress in the Research on Atmospheric Electric Field Anomaly as an Index for Short-Impending Prediction of Earthquakes, *J. Earthquake Predict. Res.*, 2000, vol. 8, no. 3, pp. 241–255.

Hobara, Y. and Parrot, M., Ionospheric Perturbations Linked to a Very Powerful Seismic Event, *J. Atmos. Sol.–Terr. Phys.*, 2005, vol. 67, no. 7, pp. 677–685.

Ismaguilov, B.S., Kopytenko, Yu.A., Hattori, K., and Hayakava, M., Gradients and Phase Velocities of ULF Geomagnetic Disturbances Used to Determine the Source of an Impending Strong Earthquake, *Geomagn. Aeron.*, 2006, vol. 46, no. 3, pp. 423–430 [*Geomagn. Aeron.* (Engl. transl.), 2006, vol. 46, pp. 403–410].

Kopylova, G.N. and Serafimova, Yu.K., Medium-Term Precursors of Kamchatka Earthquakes as a Manifestation of the Interaction between Geophysical Fields, *Sb. dokl. V mezhdunar. konf. "Solnechno-zemnye svyazi i fizika predvestnikov zemletryasenii"* (Proc. 5th Int. Conference "Solar–Terrestrial Coupling and Physics of Earthquake Precursors"), Paratunka, Kamchatka Krai, 2010, Shevtsov, B.M and Bogdanov, V.V, Eds., pp. 372–376.

Korsunova, L.P. and Khegai, V.V., Seismo-Ionospheric Effects of the Strong Crustal Earthquakes in the Pacific Region, *Geomagn. Aeron.*, 2005, vol. 45, no. 5, pp. 706–711 [*Geomagn. Aeron.* (Engl. transl.), 2005, vol. 45, pp. 665–670].

Korsunova, L., P., Khegai V. V. Medium-Term Ionospheric Precursors to Strong Earthquakes, *Int. J. Geomagn. Aeron.*, 2006, vol. 6, p. GI3005; doi:10.1029/2005GI000122.

Korsunova, L.P. and Khegai, V.V., Analysis of Seismoionospheric Disturbances at the Chain of Japanese Stations for Vertical Sounding of the Ionosphere, *Geomagn. Aeron.*, 2008, vol. 48, no. 3, pp. 407–415 [*Geomagn. Aeron.* (Engl. transl.), 2008, vol. 48, pp. 392–399].

Korsunova, L.P. and Khegai, V.V., Variations in the Surface Atmospheric Electrostatic Fields during Preparation of Crustal Earthquakes in Japan and Continental China, *Sb. dokl. V mezhdunar. konf. "Solnechno-zemnye svyazi i fizika predvestnikov zemletryasenii"* (Proc. 5th Int. Conference "Solar–Terrestrial Coupling and Physics of Earthquake Precursors"), Paratunka, Kamchatka Krai, 2010, Shevtsov, B.M and Bogdanov, V.V., Eds., pp. 383–386.

Korsunova, L.P., Mikhailov, Yu.M., Khegai, V.V., Leshchenko, L.N., Smirnov, S.E., and Bogdanov, V.V., Experimental Evidence of the Correlation between Possible Precursors of Earthquakes in Near Surface Quasistatic Electric Fields and in the Ionosphere, *Geomagn. Aeron.* (Engl. transl.), 2010a, vol. 50, pp. 920–926.

Korsunova, L.P., Chistyakova, L.V., and Khegai, V.V., Effects in the Sporadic *E* Layer during the Earthquake Preparation on August 27, 2008, according to the Observations in Irkutsk, in *Solnechno-zemnaya fizika* (Solar–Terrestrial Physics), Novosibirsk: SO RAN, 2010b, vol. 129, issue 16, pp. 149–153.

Liperovskii, V.A., Pokhotelov, O.A., and Shalimov, S.L., *Ionosfernye predvestniki zemletryasenii* (Ionospheric Precursors of Earthquakes), Moscow: Nauka, 1992.

Liu, J.Y., Chen, Y.I., Chuo, Y.J., and Chen, C.S., A Statistical Investigation of Preearthquake Ionospheric Anomaly, *J. Geophys. Res.,* 2006, vol. 111, p. A05304; doi:10.1029/2005JA011333.

Mikhailov, Yu.M., On the Properties of Earthquake Precursors in the Electrostatic Field of the Surface Atmosphere, *Phys. Solid Earth*, 2007, vol. 43, no. 4, pp. 336–339.

Ondoh, T., Anomalous Sporadic-*E* Layers Observed before *M* 7.2 Hyogo-Ken Nanbu Earthquake; Terrestrial Gas Emanation Model, *Adv. Polar Upper Atmos. Res.*, 2003, no. 17, pp. 96–108.

Oyama, K.-I., Kakinami, Y., Liu, J.Y., Abdu, M.A., and Cheng, C.Z., Latitudinal Distribution of Anomalous Ion Density as a Precursor of a Large Earthquake, *J. Geophys. Res.*, 2011, vol. 116, p. A04319; doi:10.1029/2010JA015948.

Perrone, L., Korsunova, L.P., and Mikhailov, A.V., Ionospheric Precursors for Crustal Earthquakes in Italy, *Ann. Geophys.*, 2010, vol. 28, no. 4, pp. 941–950.

Pulinets, S.A. and Boyarchuk, K.A., *Ionospheric Precursors of Earthquakes*, Berlin: Springer, 2004.

Sidorin, A.Ya., Dependence of the Occurrence Time of Earthquake Precursors on the Epicentral Distance, *Dokl. Akad. Nauk SSSR*, 1979, vol. 245, no. 4, pp. 825–828.

Sidorin, A.Ya., *Predvestniki zemletryasenii* (Earthquake Precursors), Moscow: Nauka, 1992.

Silina, A.S., Liperovskaya, E.V., Vasil'eva, N.E., and Alimov, O.A., Effect of the Earthquake Preparation Processes on Variations in the Sporadic Ionospheric *E* Layer, *Sb. dokl. V mezhdunar. konf. "Solnechno-zemnye svyazi i fizika predvestnikov zemletryasenii"* (Proc. 5th Int. Conference "Solar–Terrestrial Coupling and Physics of Earthquake Precursors"), Paratunka, Kamchatka Krai, 2010, Shevtsov, B.M and Bogdanov, V.V., Eds., pp. 440–444.

Smirnov, S.E., Characteristics of Negative Anomalies in the Quasistatic Electric Field in the Near-Earth Atmosphere on Kamchatka, *Geomagn. Aeron.*, 2005, vol. 45, no. 2, pp. 282–287 [*Geomagn. Aeron.* (Engl. transl.), 2005, vol. 45, pp. 265–269].

Xia, C., Yang, S., Xu, G., Zhao, B., and Yu, T., Ionospheric Anomalies Observed by GPS TEC Prior to the Qinghai–Tibet Region Earthquakes, *Terr. Atmos. Ocean. Sci.*, 2011, vol. 22, no. 2, pp. 177–185; doi:10.3319/TAO.2010.08.13.01(TibXS).

Zubkov, S.I., Occurrence Time and Manifestation Zone Radius for the Electrotelluric Precursor Depending on the Earthquake Energy, *Fiz. Zemli*, 1983, no. 4, pp. 101–105.

Zubkov, S.I., Origination Times of Earthquake Precursors, *Izv. Akad. Nauk SSSR, Fiz. Zemli*, 1987, no. 5, pp. 87–91.

Zubkov, S.I. and Migunov, N.I., On the Occurrence Time of Earthquake Electromagnetic Precursors, *Geomagn. Aeron.*, 1975, vol. 15, no. 6, pp. 1070–1074.