MODIFICATION OF THE IONOSPHERE BEFORE THE STRONG EARTHQUAKE OF JANUARY 13, 2007 WITH MAGNITUDE $M = 8.1$: AN INTEGRATED APPROACH

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A study was carried out of vertical sounding data collected by two ground-based vertical ionosondes Wakkanai and Kokubunji, situated within the preparation zone of an earthquake with a magnitude of $M = 8.1$, which occurred on January 13, 2007 at 04:23:21 UT east of Simushir Island and was the second of a sequence of two strong ($M > 8$) earthquakes on November 15, 2006 and January 13, 2007, which were unique events in the seismic history of the Middle Kuril Islands. A comprehensive analysis of ionospheric data showed that 13-14 hours before this earthquake, specific anomalies in the *E*- and *F*-regions of the ionosphere were simultaneously observed over both ionospheric stations, which, with a high degree of probability, were its short-term ionospheric precursors. It is shown that additional consideration when analyzing ionospheric data of the behavior of the Barbier δ-parameter, constructed on their basis, significantly increases the correctness of identification of detected ionospheric earthquake precursors in complex situations.

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1. INTRODUCTION

Well-verified cases of detection of ionospheric earthquake precursors (IEP) for strong seismic events with large magnitude (M) are very important both for clarifying the fundamental mechanisms of lithospheric-ionospheric connections and for subsequent practical tasks of successfully predicting them using ionospheric data. On the other hand, major earthquakes (with magnitude $M \geq 7.0$) occur quite rarely, and such earthquakes happen no more than 20 times a year worldwide (see the work [Khegai et al., 2022]). Earthquakes with magnitude $M \geq 8.0$ occur approximately an order of magnitude less frequently, usually no more than 2 events per year. Indeed, according to the United States Geological Survey (USGS) data from 2000 to 2021 (see (https://www.usgs.gov/programs/earthquake-hazards/lists-maps-and-statistics)), earthquakes of such strength occurred 4 times in 2007 and 3 times in 2021, in the remaining years of this period - no more than 2 per year. In total, for the period from 2000 to 2021, i.e., for 22 years, only 27 earthquakes of this class occurred, so the average frequency is $27/22 \cong 1.23$, i.e., close to one. According to estimates made in the work [Khegai, 2013], the duration of the "maturation" of an earthquake focus with $M = 8.0$ from the beginning of the growth of the focus "seed" to the moment of the shock is ~27 years. Thus, studies of ionospheric effects possibly associated with the preparation processes of major earthquakes and serving as their precursors are of great interest, including because the destructive power of such earthquakes is especially great when their hypocenters (h_G) lie at shallow depths ($h_G \leq 60$ km).

The earthquake with $M = 8.1$ (detailed description is given in [Rogozhin and Levina, 2007]) occurred on January 13, 2007, at 04:23:21 UT (or 13:23:21 LT) to the east of the Kuril Islands, with geographic coordinates of its epicenter: latitude $\varphi_e = 46.24°$N; longitude $\lambda_e = 154.52°$E, and hypocenter depth $h_G = 10$ km, i.e., according to the classification in the monograph [Aprodov, 2000], this earthquake is classified as superficial (or crustal). In [Oyama et al., 2016], this earthquake was included in a series of events for which ionospheric effects in the Total Electron Content (TEC) before the earthquakes were examined using statistical methods, following the approach , proposed by the researchers [Liu et al., 2004; 2013; 2014]. The authors showed that for events with $M > 7.0$ (unlike the range $6.0 \leq M < 7.0$), it is difficult to obtain clear identification of ionospheric precursors using statistical methods, and they suggested considering such events individually. It should be noted that specifically for this earthquake, [Saha et al., 2014] were able to identify anomalous variations in a low-frequency signal at 40 kHz one day before the shock on a radio path crossing the preparation zone.

In this paper, a comprehensive study of ionospheric data from two ground-based vertical ionosphere sounding stations (VISS, hereinafter, where possible, simply "stations" or "st.") Wakkanai (geographic coordinates $\varphi = 45.16°$ N; $\lambda = 141.75°$ E) and Kokubunji (geographic coordinates $\varphi = 35.71°$ N; $\lambda = 139.49°$ E), located in the preparation zone of the specified earthquake, was conducted during the six days preceding the moment of the shock and on the day of the earthquake (the seventh). The aim of the study was to identify its possible ionospheric precursors, taking into account the characteristics of solar and geomagnetic activity during the considered time period.

It should be noted that variations in the ionosphere in the specified geographic region before the first Simushir earthquake are not considered in this work. The fact is that shortly before it, on November 10, 2006, an extremum of the DST-index ($DST_{\text{extr}} = -60$ nT) was recorded, and the value of the Kp-index reached 6_0, which according to the classification in [Loewe and Prölss, 1997] corresponds to a moderate geomagnetic storm. Moreover, approximately 10 hours before the shock, a surge in auroral activity was also observed, when the value of the AE-index was 450 nT. In this regard, possible ionospheric effects of the preparation of the first Simushir earthquake may overlap with ionospheric effects caused by geomagnetic disturbances, which significantly complicates the unambiguous identification of a possible ionospheric precursor for this earthquake.

2. DATA ANALYSIS, DISCUSSION AND RESULTS

The characteristic scale of the earthquake preparation area on the earth's surface is defined as the radial distance from the earthquake epicenter to the boundary of its preparation zone and depends on its magnitude M. Various (empirical and theoretical) estimates of this scale (in km) appear in the scientific literature, as presented in works [Dobrovolsky et al., 1979; Sidorin, 1992; Bowman et al., 1998; Hao et al., 2000]. Further, we will use the minimum estimate of this scale, obtained in [Dobrovolsky et al., 1979], derived under the condition when the depth of the earthquake hypocenter h_G approaches zero. In this case, the characteristic size of the earthquake preparation zone on the earth's surface is expressed by the formula $R_{\text{Dobrovolsky}} = R_D = 10^{0.43M}$ (km). In this case, for an earthquake with $M = 8.1$, $R_D(M = 8.1) = 10^{0.43\times 8.1} = 3040$ km ≈ 3000 km. Thus, possible IEP (Ionospheric Earthquake Precursors) of this earthquake should manifest in the ionosphere within a circle with a radius of 3000 km, with the center determined by the geographical coordinates of the earthquake epicenter. This situation is illustrated in Fig. 1.

Fig.1.

Fig. 1 shows the geographical position of the earthquake epicenter with $M = 8.1$, which occurred on January 13, 2007 (triangular star), as well as the location of ionospheric stations Wakkanai and Kokubunji (black circles). Epicentral distances to the stations along the great circle arc are indicated near the corresponding arrows, and the radius of the preparation zone $R_D \approx 3000$ km is shown above the figure. Thick solid lines define the positions of plate boundaries in the lithosphere absorption area (see also the monograph [Aprodov, 2000]), thin solid lines outline the islands of the Japanese archipelago. The figure clearly shows that the ionospheric stations are located deep within the preparation zone of this earthquake. We should also immediately note that according to The National Weather Service (NWS), U.S. (https://www.swpc.noaa.gov/products/solar-cycle-progression), the average value of the $F10.7$ index, which characterizes solar activity, in January 2007 was 83.76 SFU, and the smoothed average was 78.1 SFU, i.e., solar activity was low. Accordingly, low geomagnetic activity could be expected over a sufficiently long time interval within this month, which reduces the probability of disturbances in the ionosphere caused by magnetic storms. In Fig. 2 below, solid lines show changes in geophysical indices (panel a – Kp ; panel b – B_z-component of the interplanetary magnetic field; panel c – AE), as well as hourly variations of current critical frequencies $foF2_{cur}$ at Kokubunji station (panel d) and Wakkanai station (panel e) over a seven-day time interval from 01.07.2007 to 01.13.2007. A long vertical arrow (passing through panels d and e and crossing their x-axes) marks the moment of the earthquake, and filled rectangles below it indicate local time intervals from 18:00 to 6:00 LT. The latter is done to show when the supposed IEP (Ionospheric Earthquake Precursor) is observed – during daylight/nighttime hours. On panels d and e , the lines shown with "dots" correspond to median values for 13 geomagnetically quiet (Q) days of January ($foF2_{med\,Q}$), when throughout the whole day the Kp -index did not exceed 2_+ (this level is also marked on panel a by a horizontal dash-dotted line), and dash-dotted lines define the interval $foF2_{med\,Q} \pm 1.5\,IQR$ (IQR – the difference between the upper (75%) and lower (25%) quartiles, i.e., Inter Quartile Range). Areas with dark fill where $foF2_{cur}$ exceeds $foF2_{med\,Q}$ are marked with arrows as possible IEPs, and small rectangles of the same color near the x-axes correspond to time intervals when both stations simultaneously observed F -scattering and the sporadic Es layer.

Fig. 2.

As mentioned above, in our work, the interquartile range $foF2_{cur}(t_i)$ due to random deviations. Then the band IQR based on the selected set of geomagnetically quiet days was chosen as a measure of dispersion in the behavior of $K_{\pm} = foF2_{med}(t_i) \pm 1.5\,IQR(t_i)$ will limit the amplitude of variations $foF2_{current}(t_i)$, explained by random deviations, with a certain degree of probability. According to K ł otz and Johnson [1983], in the case of a normal distribution of "errors" in values $\Delta foF2(t_i)$, the value of $1.5\, IQR(t_i)$ will correspond to approximately two standard deviations, and the values of $foF2_{cur}(t_i)$ under the influence of various random factors should fluctuate within the band $K_{\pm}$ with a probability of 95%. Therefore, values of $foF2$ that go beyond the specified band can be classified as anomalous values of $foF2_{cur}(t_i)$

It should be noted that successful identification of seismic-ionospheric anomalies in the behavior of the critical frequency of the $F2$-layer of the ionosphere based on IQR as a measure of deviation from the background was previously performed, in particular, in the work of [Liu et al., 2006], with the difference that the value of $IQR/2$ was used as the initial measure of deviation from the background. Thus, we use a stricter criterion for selecting deviations that can be attributed to disturbed values of the parameters under consideration.

Let's discuss Fig. 2 in more detail. First, it can be seen that throughout the shown time interval, the geomagnetic environment corresponds to quiet conditions, as the level of planetary geomagnetic activity (panel *a*) mainly corresponds to values of $Kp \leq 2_+$, only twice reaching levels $3_{\text{and}} 3_0$ for three hours. Before the day of the earthquake (January 12), this level drops to values of 0_+ at 3 UT, and at 18 UT decreases to 0_0 and remains so until the end of the entire observation interval. Second, the magnitude of the B_z component of the interplanetary magnetic field (panel *b*) throughout the observation interval lies in the range from -3 nT to 5 nT, i.e., -3 nT $\leq B_z <$ 5 nT. Finally, a brief insignificant exceeding of the 300 nT level by the AE index (panel *c*) occurs three days before the shock (January 10). Thus, throughout the considered time interval, the geomagnetic environment according to all the specified geomagnetic indices corresponds to a quiet level. Therefore, disturbances in the ionosphere that might be caused by geomagnetic disturbances should not be observed.

Now let's consider the features of variations in $foF2_{cur}$, marked with arrows (shaded areas in Fig. 2) as possible IPZ, in the interval from 13 UT to 17 UT on January 12, the day before the shock (panels *g*, *d*). It can be seen that at the Wakkanai station closer to the epicenter R_e(Wak) $\cong$ 1000 km], the magnitude of the positive deviation $\delta_{foF2}(\text{Wak})_{max} = [100 \times (foF2_{cur} - foF2_{med\,Q}) / foF2_{med\,Q}]_{max} \cong 16\%$ is greater than $\delta_{foF2}(\text{Kok})_{max} \cong 11\%$ at the Kokubunji station located farther from it R_e(Kok) $\cong$ 1700 km] in this time interval. Simultaneously, it can be seen that for the Wakkanai station, the current value of $foF2_{cur}$(Wakkanai) lies at the upper boundary of the dispersion $foF2_{med\,Q} + 1.5\, IQR$. Exceeding this boundary means that with approximately 95% probability, such a deviation is non-random in nature (see above, and in more detail - page 534 of the work [Bychkov et al., 2017]). At the Kokubunji station, this excess of median values $foF2_{med\,Q}$(Kok) by current values $foF2_{cur}$(Kok) is not so significant. However, in the case under consideration, there is also a simultaneous registration near the time 15 UT on 12.01.2007 (00 LT on 13.01.2007) of a sporadic layer *Es* and F-scattering (F-spread) at both stations, separated from each other by ≅ 1068 km along a great circle arc, according to data from [https://wdc.nict.go.jp/IONO/HP2009/contents/Ionosonde_Map_E.html]. The presence of simultaneous existence of these structures above both ionospheric stations is illustrated by Fig. 3, which presents ionograms for the time 15 UT on 12.01.2007.

Fig. 3.

As can be seen from the figure, the intensity of these structures' manifestation in the ionosphere is higher for the Wakkanai station, which is closer to the earthquake epicenter. In [Korsunova and Legenka, 2021], the main criterion for identifying short-term IPS was the simultaneous appearance of anomalous deviations in ionospheric parameters at separated (by hundreds of kilometers or more) ionospheric stations within the preparation zone of a specific earthquake. The pattern presented in Fig. 3 satisfies this criterion.

Let us now use another parameter for further analysis of the ionospheric situation before the earthquake of 13.01.2007 - the Barbier δ-parameter ($\delta_{Barbier}$). This parameter was first defined based on the semi-empirical Barbier formula [Barbier, 1957; Barbier and Glaume, 1962; Barbier et al., 1962] in the work [Pulinets et al., 2022] and used for the analysis of ionospheric disturbances and the search for IPS. In [Pulinets et al., 2023], its effectiveness in searching for IPS was demonstrated, and the latitudinal range for which the use of the combined parameter $\delta_{Barbier}$ in searching for IPS was verified extends from ~20.0° N to ~54.0° N. Limitations in using the $\delta_{Barbier}$ parameter are related to the fact that it is physically well-defined only for unilluminated local time hours in the interval 20-04 h LT. The mathematical expression for $\delta_{Barbier}$ appears as follows (see formula (2) in [Pulinets et al., 2022])

$$\delta_{Barbier} \equiv foF2_{cur} / foF2_{med}]^{2} \exp[(h'F_{med} - h'F_{cur}) / H)] - 1, \qquad (1)$$

where the subscripts "cur" and "med" refer to the current values of the corresponding quantities and their median values for the selected ensemble of reference days.

Here $foF2$ is the critical frequency of the $F2$ layer of the ionosphere (MHz), $h'F$ is the minimum virtual height of the reflection trace of the ordinary wave from the entire F region of the ionosphere (km) according to the definition given in the book [Manual ..., 1977], § 1.3., p. 1.32, page 33. The characteristic scale H (in km) for any specific ionospheric station, in accordance with its geographical location and time, can be calculated using the well-developed and modern neutral atmosphere model NRLMSISE-00 [https://ccmc.gsfc.nasa.gov/modelweb/models/nrlmsise00.php] for a set of reference days according to a specified procedure (for details, see [Pulinets et al., 2022]).

The relative complex parameter $\delta_{Barbier}$ defined in this way characterizes the change in the intensity of atmospheric airglow at a wavelength of 630 nm during dark hours, as estimated from ionospheric data. The fact is that (see, for example, the work of [Chattopadhyay and Midya, 2006]), for this red line of oxygen emission OI 630 nm, from experimentally determined values of various rate constants, quenching coefficients, and transition probabilities, it can be derived that the emission intensity in this line is proportional only to the electron concentration and, thus, the nature of the change in the intensity of the OI 630 nm emission is mainly determined by the altitude profile of the electron concentration (N_e), i.e., the critical frequency $foF2$. Then it turns out that if $\delta_{Barbier} > 0$, the estimated emission intensity is above its median level, and if $\delta_{Barbier} < 0$, the estimated emission intensity is below this level. The smaller the value of $h'F_{cur}$ compared to $h'F_{med}$, the higher the probability that the estimated intensity of the emission in the OI 630 nm line will exceed its median level, since in expression (1) their difference determines a factor with exponential growth, which makes this parameter very sensitive to changes in $h'F_{cur}$.

Fig. 4.

In Fig. 4, panel *b* repeats panel *d* of Fig. 2 with the same designations, and panel *a* shows the behavior of parameter $\delta_{Barbier}$ during non-illuminated hours (20-04 h LT). The horizontal line (dots) corresponds to median values over the selected seven-day interval, and the dash-dotted lines mark the levels $K_{\pm} = (\delta_{Barbier})_{MED} \pm 1.5\ IQR$. The dark filling on panel *a* marks the probable short-term IPP (ionospheric precursor) of the earthquake 13-14 hours before the shock.

Due to the high sensitivity of the $\delta_{Barbier}$ parameter, it can be seen that it significantly exceeds the specified upper boundary of dispersion at 13 and 14 UT on 12.01.2007, with the excess occurring within the range of 13 - 17 UT on 12.01.2007 when a positive disturbance of $foF2_{cur}$ (Wakkanai) is observed. Unfortunately, for Kokubunji station, it was not possible to construct a similar picture due to the lack of necessary data on $h'F$ in the corresponding time interval.

In conclusion, the following should be noted. The anomalous variations of the low-frequency signal at 40 kHz identified on 12.01.2007, one day before the earthquake on the radio path passing over its preparation zone in the study [Saha et al., 2014], were observed in the time interval from 8 to 17 h UT (see Fig. 4 of [Saha et al., 2014]). This time interval includes the narrower interval from 13 to 17 h UT that we identified, when the IPPs we detected were observed at Wakkanai and Kokubunji stations.

3. CONCLUSIONS

As a result of the comprehensive study of ionospheric data from two ground-based vertical sounding ionosphere stations, Wakkanai and Kokubunji, located in the preparation zone of the earthquake with magnitude *M* = 8.1, which occurred on January 13, 2007, at 04:23:21 UT east of the Kuril Islands, the following conclusions can be drawn **.**

1. Comprehensive analysis of ionospheric data shows that 13-14 hours before this earthquake, specific anomalies in the *E and иF regions* of the ionosphere were simultaneously observed over both ionospheric stations, which, with a high degree of probability (according to the authors), can be identified as its short-term ionospheric precursors.

2. Additional consideration when analyzing ionospheric data of the behavior of the Barbier δ-parameter (δ_{Barbier}), constructed on their basis, significantly increases the accuracy of identification of detected ionospheric earthquake precursors in complex situations.

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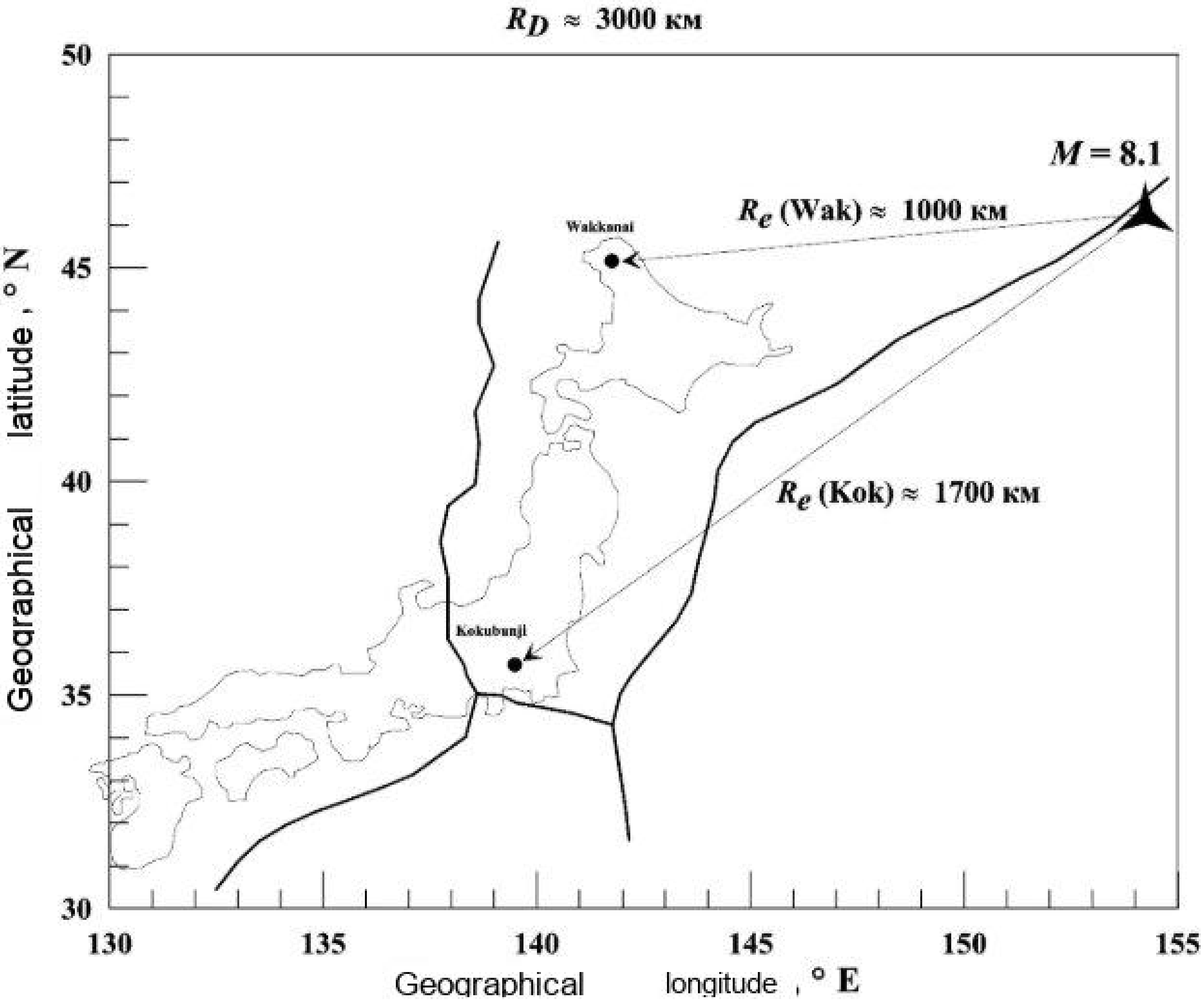
Figure Captions

Fig. 1. Geographical locations of the epicenter of the earthquake with $M = 8.1$, which occurred on January 13, 2007 (triangular star), as well as the ionospheric stations Wakkanai and Kokubunji (black circles). Epicentral distances to the stations along the great circle arc are indicated near the corresponding arrows, and the radius of the preparation zone $R_D \approx 3000$ km is shown above the figure. Thick solid lines define the positions of plate boundaries in the lithosphere subduction area, and thin solid lines outline the islands of the Japanese archipelago.

Fig. 2. Changes (solid lines on all panels) of geophysical indices (a) – Kp ; (b) – B_z-component of the interplanetary magnetic field; (c) – AE), as well as hourly variations of current critical frequencies $foF2_{cur}$ at Kokubunji station (d) and Wakkanai station (e) over a seven-day time interval from 01.07.2007 to 01.13.2007. The long vertical arrow (passing through panels d and e and crossing their abscissa axes) marks the moment of the earthquake, and the blackened rectangles below it indicate local time intervals from 18:00 to 6:00 LT. On panels d and e , the lines with "dots" correspond to median values for 13 geomagnetically quiet (Q) days of January ($foF2_{med\,Q}$), when throughout the entire day the Kp-index did not exceed 2 Kp -index did not exceed 2_+ , and dash-dotted lines define the interval $foF2_{med\,Q} \pm 1.5\,IQR$. The areas with dark filling where $foF2_{cur}$ exceeds $foF2_{med\,Q}$ are marked with arrows as possible EPI (earthquake precursor ionospheric), and small rectangles of the same color near the abscissa axes correspond to time intervals when F -spread and sporadic layer Es were synchronously observed at both stations.

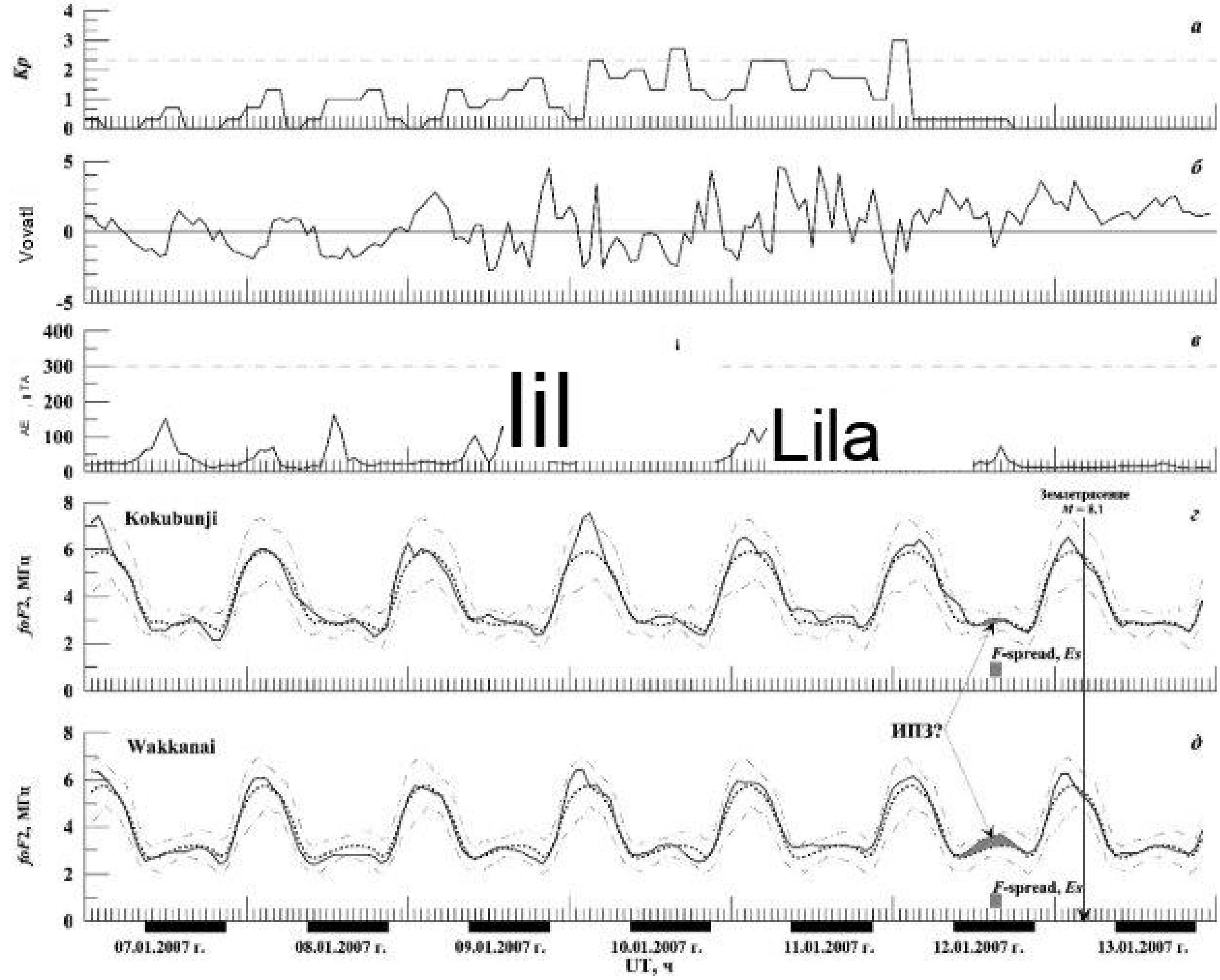
Fig. 3. Ionograms of Wakkanai station (upper panel) and Kokubunji station (lower panel) at 15:00 UT on 12.01.2007. Sporadic layer Es and F -spread are observed at both stations.

Fig. 4. Panel (a) shows the behavior of the $\delta_{Barbier}$ parameter during dark hours. The horizontal line (dots) corresponds to median values for the selected seven-day interval, and the dash-dotted lines mark the levels $K_{\pm} = (\delta_{Barbier})_{MED} \pm 1.5\,IQR$. The dark filling on panel a indicates a probable short-term EPI 13-14 hours before the earthquake. Panel b repeats panel e of Fig. 2 with the same notations.



$R_D \approx$ 3000 км
$M = 8.1$
R_e (Wak) ≈ 1000 км
R_e (Kok) ≈ 1700 км
Wakkanai
Kokubunji
50
45
40
35
30
130
135
140
145
150
155
Geographical latitude , ° N
Geographical longitude , ° E

Fig. 1.



Kp
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Землетрясение
г
foF2, МГц
F-spread, Es
НПЗ?
Wakkanai
д
foF2, МГц
F-spread, Es
07.01.2007 г.
08.01.2007 г.
09.01.2007 г.
10.01.2007 г.
11.01.2007 г.
12.01.2007 г.
13.01.2007 г.
UT, ч

Fig. 2.

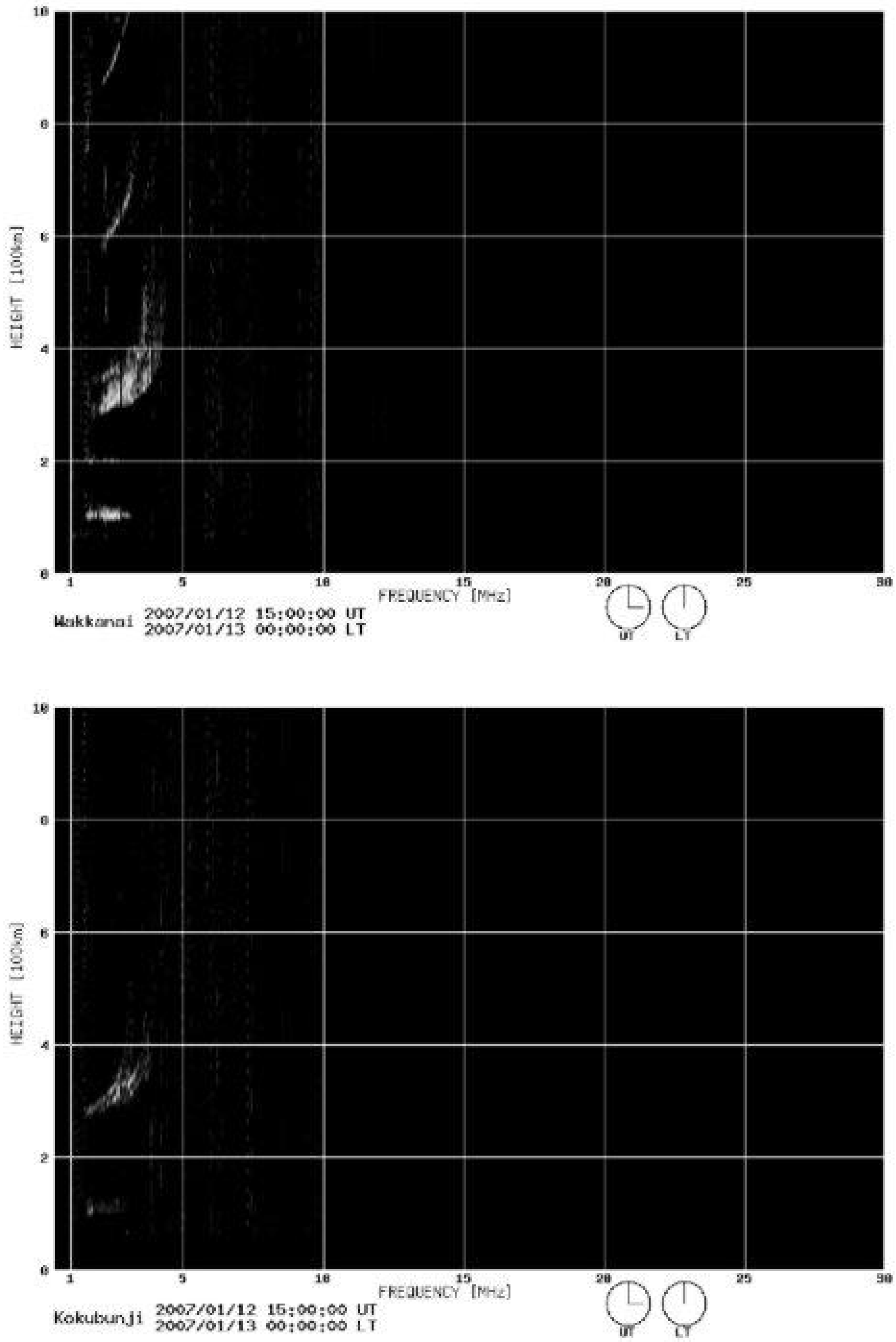
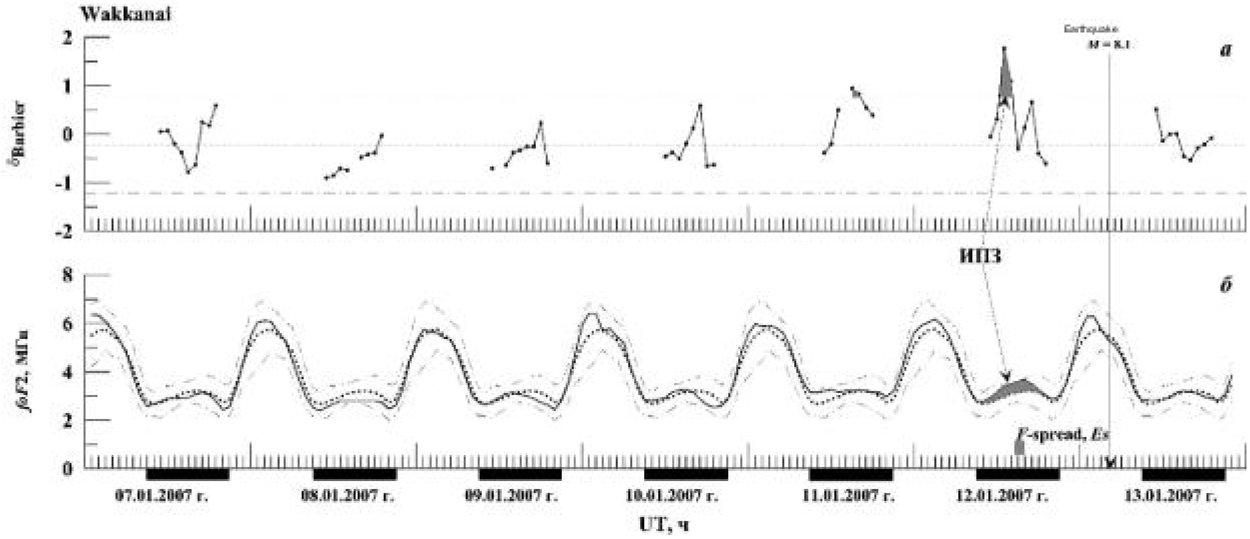

HEIGHT [100km]
FREQUENCY [MHz]
Wakkanai 2007/01/12 15:00:00 UT
2007/01/13 00:00:00 LT
UT
LT
HEIGHT [100km]
FREQUENCY [MHz]
Kokubunji 2007/01/12 15:00:00 UT
2007/01/13 00:00:00 LT
UT
LT

Fig. 3.



Wakkanai
Earthquake
M = 8.1
а
δBarbier
ИПЗ
б
foF2, МГц
F-spread, Es
07.01.2007 г.
08.01.2007 г.
09.01.2007 г.
10.01.2007 г.
11.01.2007 г.
12.01.2007 г.
13.01.2007 г.
UT, ч

Fig. 4.