Earthquake precursors in the F-region of the ionosphere, statistics of seismoionospheric effects according to the data of vertical ionospheric sounding stations of Japan

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Object of the study: variability of critical frequency foF2~√Nmax in connection to Eqs.

A few words on the literature data about the magnitude of Eqs, time of manifestation, amplitude effects observed, distance from the epicenter and the signs of the anomalies.

Magnitude Eq: as a rule, M6+.

Anomaly time: as a rule, 5 days before and 5 days after Eq, very rare 10-15 days;

Amplitude: mainly few percent, but sometimes splashes up to 25% and even to 40% were observed;

Depth Eq: as a rule, less than 40-60 km;

Distance from epicenter: as a rule, several hundred km or Dobrovolsky radius $Rd=10^{0.43M}$ [Dobrovolsky et al., 1979].

Anomaly sign: both positive and negative;

The objective of this work is to statistically investigate the reliability of seismoionospheric effects in variations of the critical frequency foF2 depending on distance and depth, at distances up to 2000 km.

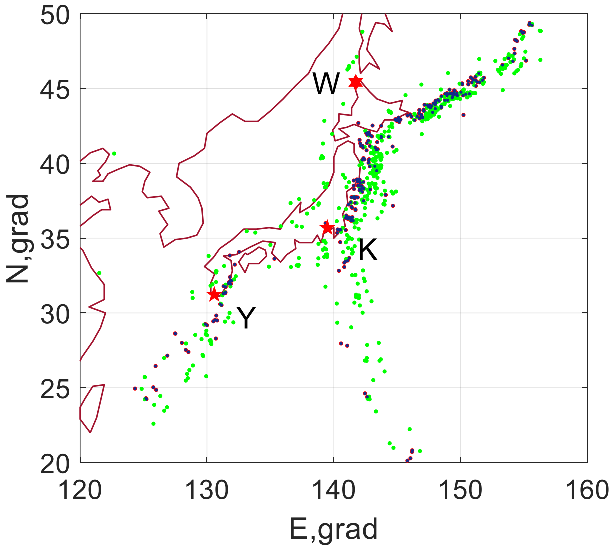


Fig. 1. Earthquake location map, green- H<35 km, blue- 35<=H<70 km, distance R<2000 km from the station **K**, M_W6+. Asterisks show station locations, **K**-Kokubunji, **W**-Wakkanai, **Y**-Yamagawa, ISC GEM, 1957 - 1975 and GCMT 1976 – 2020.

Hourly variations $\boldsymbol{\Delta fi = (foF2_i - median(foF2))/ median\ foF2}$ were examined where the *median*(*foF*2) is the median of foF2 values for (-7, +7) days around the i-th hour, which was assumed to be zero.

Days with ΣКp >25 and subsequent days were also excluded.

The shallow, intermediate depth, and the deep earthquakes are believed to origin by different physical mechanisms of failure.

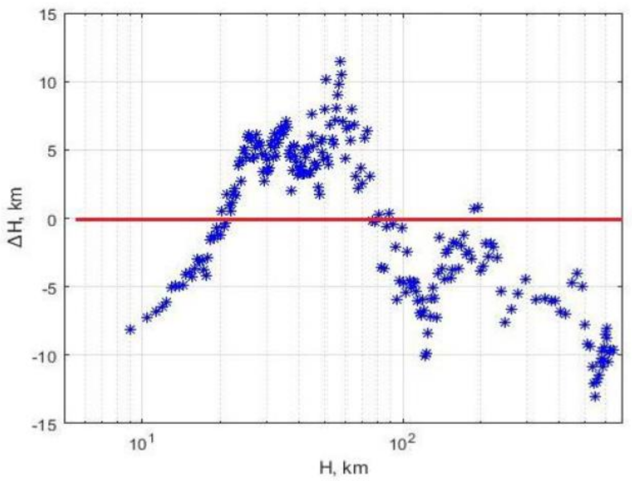
It means that their seismo-ionospheris effects could different also.

The evidence of changes in the physical mechanisms of earthquakes of different depths were obtained recently in [Rodkin, 2022].

In particular, it was shown that earthquakes with sources in the depth range, presumably associated with the high role of high-pressure fluid, are characterized by the development of the process of rupture upward - the depth of the earthquake, according to the solution of the seismic moment, on average turns out to be less than the depth of the hypocenter (the beginning of the rupture process).

Rodkin, M.V. The Variability of Earthquake Parameters with the Depth: Evidences of Difference of Mechanisms of Generation of the Shallow, Intermediate-Depth, and the Deep Earthquakes // Pure Appl. Geophys. (2022). https://doi.org/10.1007/s00024-021-02927-4].

Comparison of depth dependence from seismological and ionospheric data



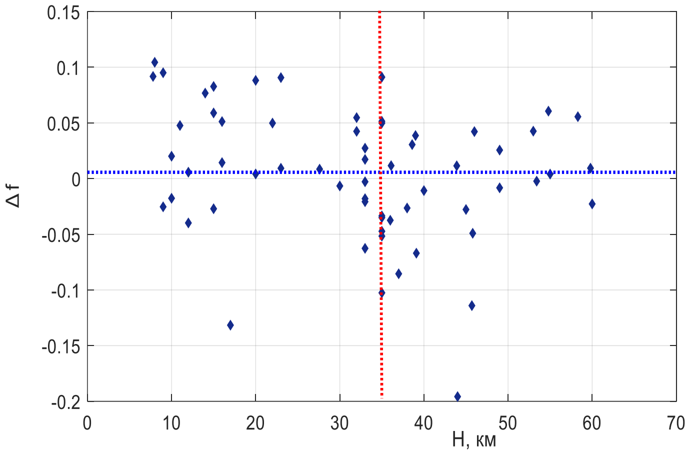


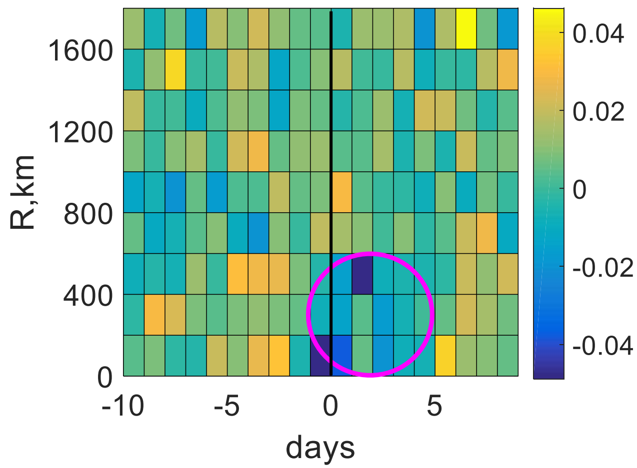
Fig. 2. Mean differences of earthquake depths estimated from hypocenter location and from seismic moment solution. The means for groups of 120 events with a step of 60 events are shown.

Fig. 3. Dependence of average Δf values on (-1) day on the depth of earthquakes M6.5+, R ≤ 500 km. The horizontal line shows the average background Δf value; vertical – approximate position of the anomaly sign change.

The predominate sign of the probable seismic-ionospheric effect for earthquakes with different physical mechanism of failure seems to be different.

Below we will consider such earthquakes separately.

The result of overlaying epochs for the interval 1957-2020, Eqs 35<=H<70



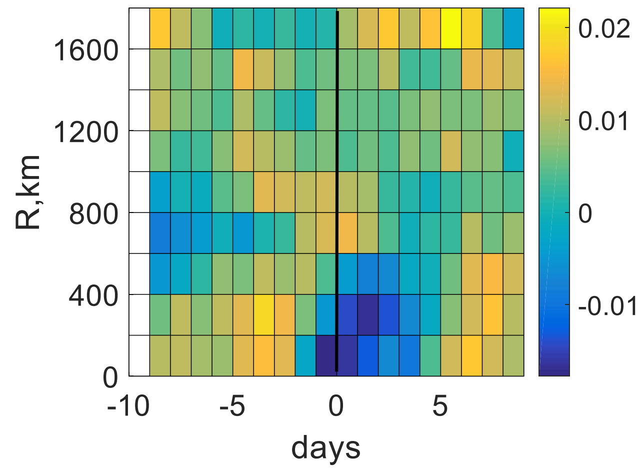


Fig. 4a. Deviations from the background value of foF2 frequencies in the vicinity of Eqs 35<=H<70 km, 1957-2020.

Fig. 4b. The same anomaly is smoothed across cells: (-1, +1) horizontally and (0,+1) vertically.

Mean amplitude of the anomaly equals 3%

77 Eqs R<600 km, 35<H<70 km, M6.0+, data is available for 47 Eqs, in (-1) day for 31 Eqs $\Delta f < mean(\Delta f)$ and for 16 Eqs $\Delta f > mean(\Delta f)$ in (-1) day, probability of casual difference P<1.5%.

The result of overlaying epochs for the interval 1957-2020, Eqs M_W6+, H<35

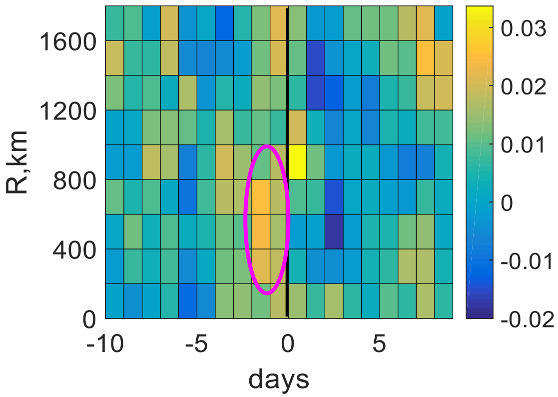


Fig. 5a. Deviations from the background value of foF2 frequencies in the vicinity of Eqs H<35 km, M6.0+ , 1957-2020.

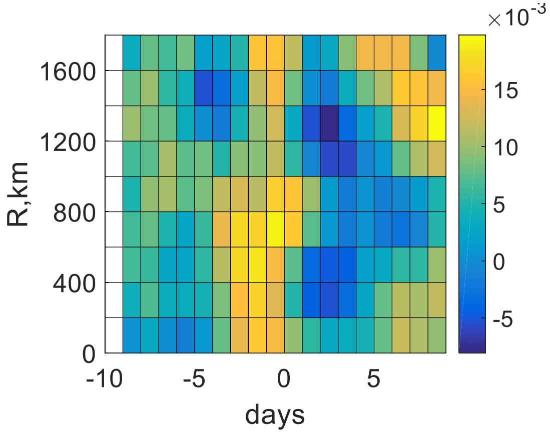


Fig. 5b. The same anomaly is smoothed across cells: (-1, +1) horizontally and (0,+1) vertically.

For the case of earthquakes with a depth H<35 km, we do not see a sufficiently obvious anomaly in the close vicinity of the epicenter.

A few possible anomalies can be seen at large spatiotemporal distances.

Let's try to choose among them the most reliable anomaly.

This is a common problem, see examples:

Shaha, M., Jin, S.: Statistical characteristics of seismo-ionospheric GPS TEC disturbances prior to global Mw ≥ 5.0 earthquakes (1998–2014). Journal of Geodynamics **92**, 42–49 (2015). https://doi.org/10.1016/j.jog.2015.10.002

The authors studied variations in TEC all over the world came to the conclusion that pre-earthquake changes in GIM-TEC data exists all over the world 1-5 days before EQs M5+.

Zhu, F., Su, F., Lin, J.: Statistical analysis of TEC anomalies prior to M6.0+ earthquakes during 2003–2014. Pure Appl. Geophys. **175**, 3441–3450 (2018).

The authors studied variations in TEC at distances (-10, +10) degrees in latitude and longitude – i.e. within a radius of about 1000 km for 1339 earthquakes with M6+, with depth H< 60 km, and came to the conclusion that «our study does not provide clear evidence of pre-earthquake changes in GIM-TEC data. However, the statistical results do not completely disapprove the possible existence of precursory».

It can be assumed that the real seismo-ionospheric anomaly should be more stable over time. Let's try to choose such less changeable component

We divide the observation interval into two parts: 1957-1988 and 1989-2020

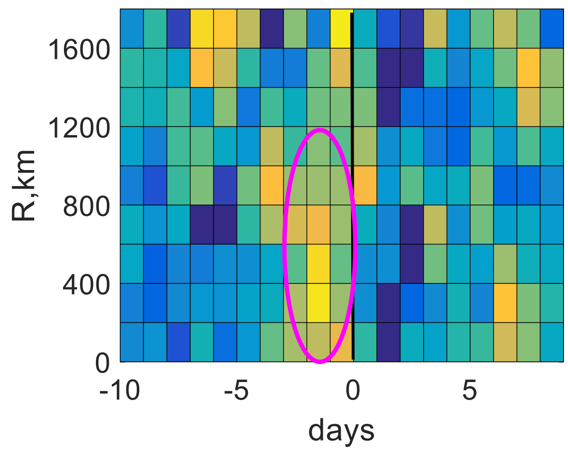


Fig. 6a. Deviations from the background value of foF2 frequencies in the vicinity of Eqs H<35 km, M6.0+, 1957-1988.

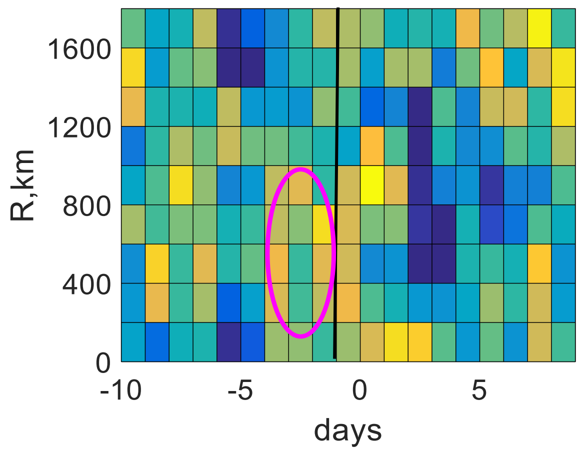
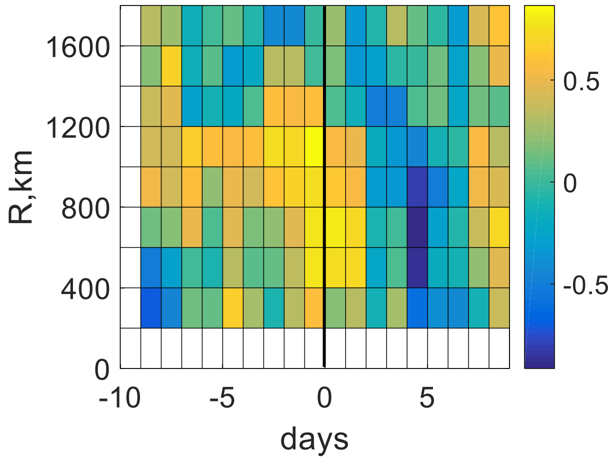


Fig. 6b. Deviations from the background value of foF2 frequencies in the vicinity of Eqs H<35 km, M6.0+, 1989-2020.

Correlation coefficients for deviations from the background value of foF2 frequencies, cell (-1, +1) by time and distance - 3*3



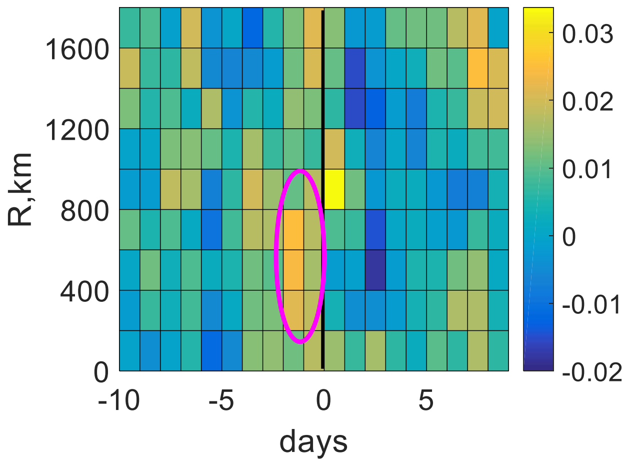


Fig.7. Values of correlation coefficients for deviations from the background value of foF2 frequencies in the vicinity of Eqs H<35 km, M6.0+, for two non-overlapping time intervals 1957-1988 and 1989-2020.

Fig. 5a. Deviations from the background value of foF2 frequencies in the vicinity of Eqs 1957-2020, H<35 km, M6.0+.

Persistent anomaly of foF2 frequencies in the vicinity of Eqs, 1957-2020, H<35 km

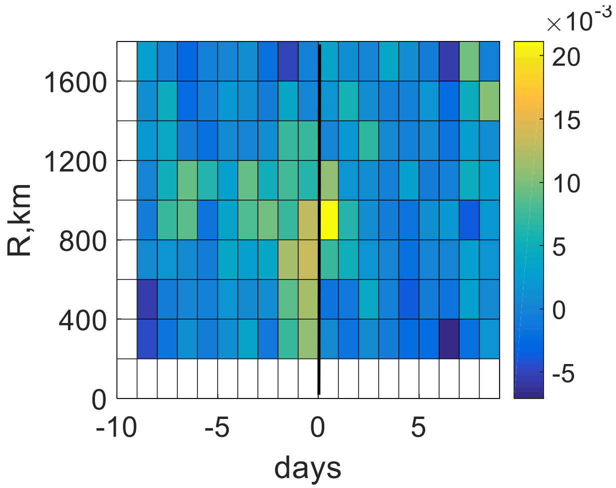


Fig. 8a. Persistent anomaly of foF2 frequencies in the vicinity of Eqs **1957-2020** H<35 km, M6.0+.

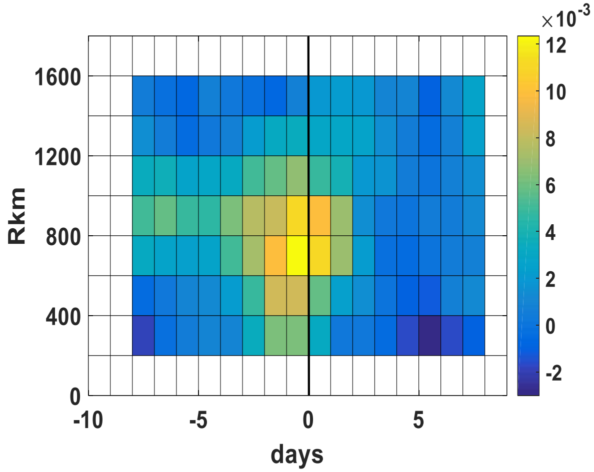
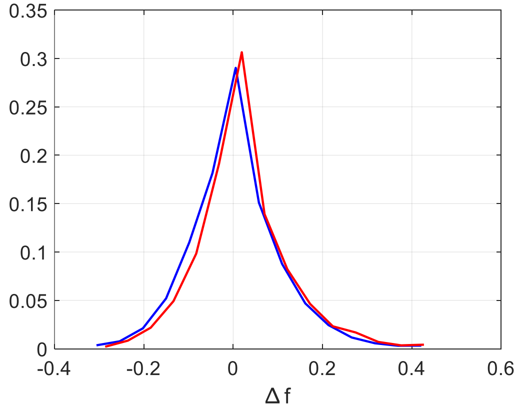
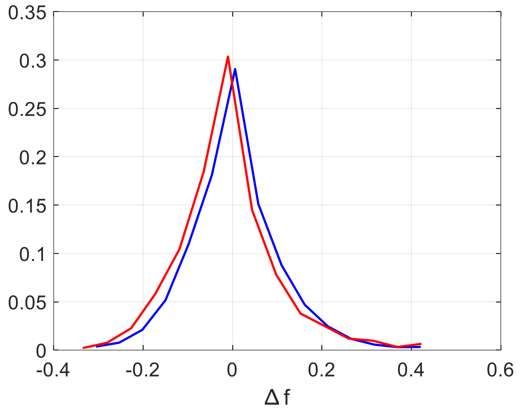


Fig. 8 b. The same anomaly is smoothed across cells: (-1, +1) horizontally and (0,+1) vertically

Mean amplitude of the anomaly equals 1.9%, 79 Eqs 600< R<1000 km, H<35 km, M6.0+, data is available for 41 Eqs, in (-2,-1) day for 30 Eqs *Δf>mean(Δf)* and for 11 Eqs *Δf<mean(Δf)* in (-2,-1) day, probability of casual difference P<1%.

The comparison of the distribution densities for "seismoionospheric variations" Δf described above with variations Δf in background time.





a) Eqs H<35 600<R<1000 km, (-2,-1) days b) Eqs 35<=H<70 km R<600 km, (-1) day

Fig. 9. Distribution density Δf, red line – seismoionospheric effect, blue line- background

These anomalies are quite statistically reliable with a probability of over 99.5% in accordance with Smirnov criterion. From a comparison of the curves for the seismic-ionospheric effect with the background in Fig. 9a, b, we obtain, that on average an increase (or decrease) in foF2 does not occur due to large positive (or negative) variations, but due to minor changes in the average value.

Simulation of a random process for EQs 35≤*H*<70 км

A decrease in foF2 over successive 5 days has been experimentally observed at 3%. Let's simulate 10 series of 77 virtual events (that's how many real events there are), and for each of them for 121 hours. reduce the foF2 frequency by 3%; for these data, we repeat the process of calculating Δf as for real earthquakes.

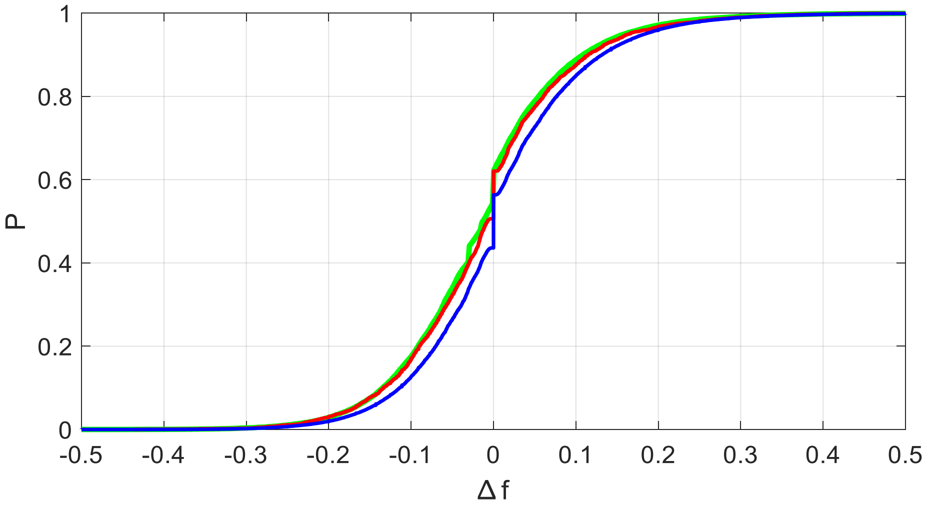


Fig. 11. Distribution functions Δf for real Eqs M6+, 35≤H≤70 km, R<600 km for (-24,…+96) hours, real 4608 values - red line; a distribution made up of 10 series of virtual events (77events, 121 hours for each event) – 48210 values, green line; background–blue line.

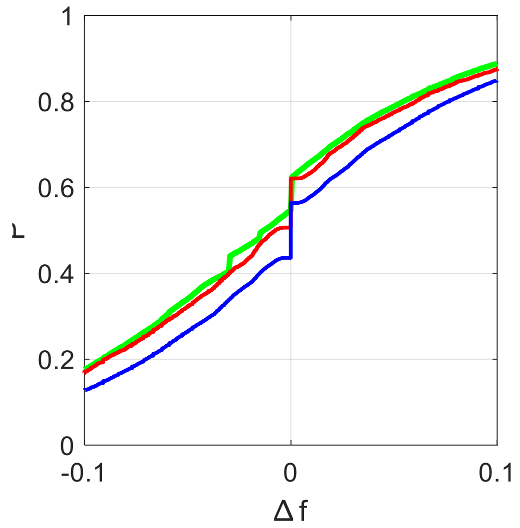
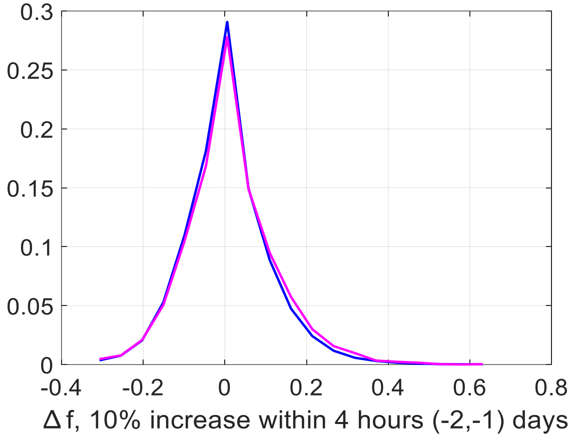


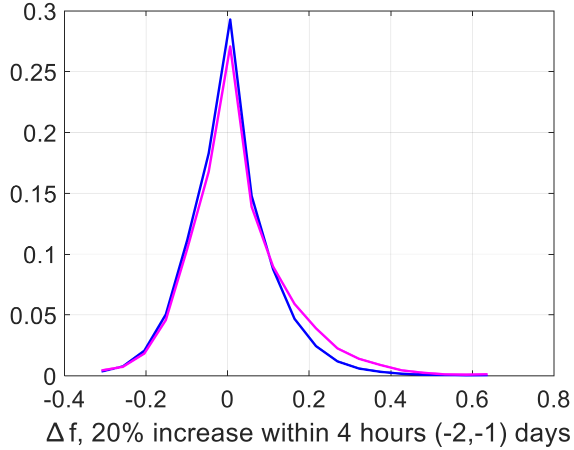
Fig. 11b. Fragment of the previous Fig 11

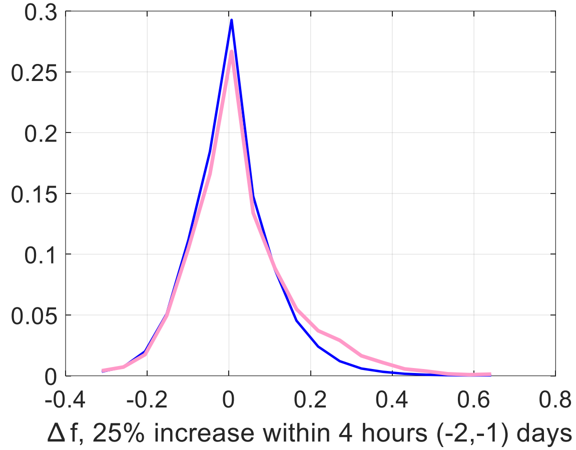
Distributions Δf of the real and the virtual Eqs may belong to the general population (with a probability of 25%), and are different from the background distribution with a probability of over 99.5% in accordance to Smirnov criterion.

We can conclude that a deviation in the foF2 value of 2-3% over several days could explain the observed anomaly. An increase (or decrease) in Nmax by 4-6% leads to an increase (or decrease) in foF2 by 2-3%.

Let us suppose, that foF2 increases by 10%, 20%, 25% over 4 hours







Mean increase 1.3%

Mean increase 2.4%

Mean increase 2.8%

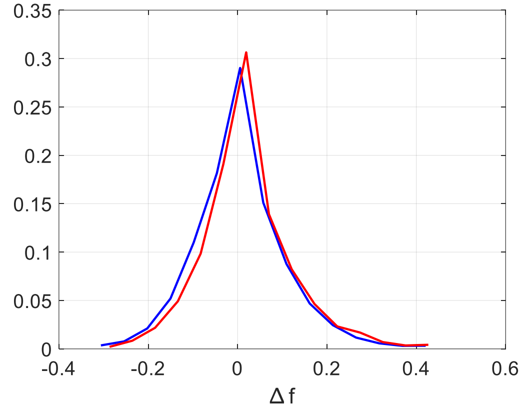


Fig.9a) Eqs H<35 600<R<1000 km, (-2,-1) days, mean increase 1.9%

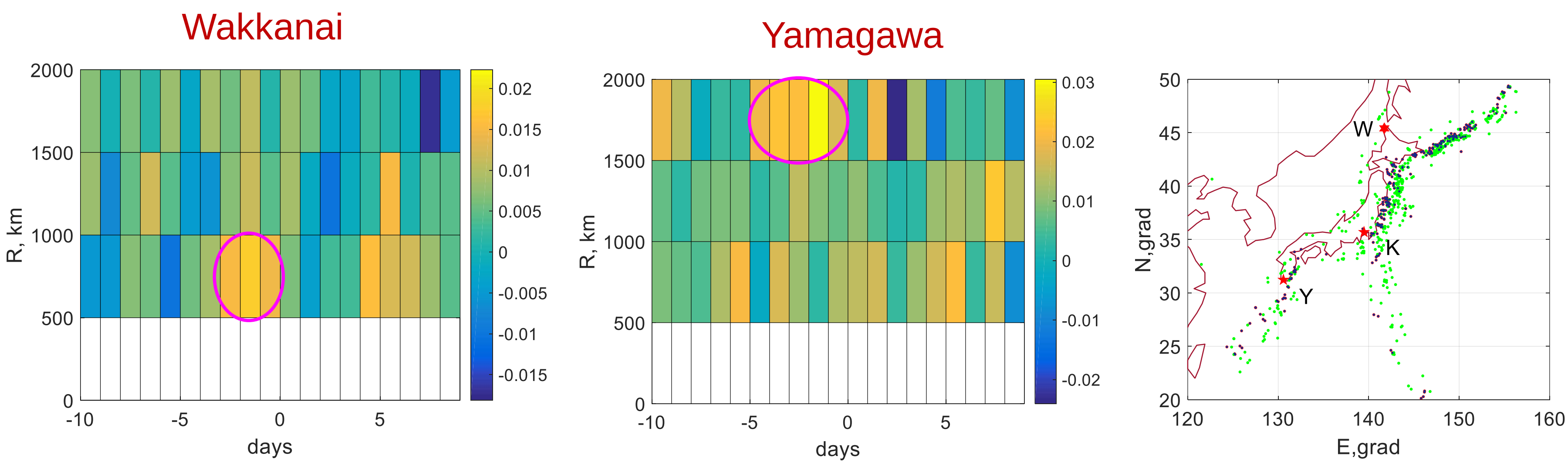


Fig. 12 Deviations from the background value of foF2 frequencies in the vicinity of Eqs H<35 km, M6.0+ 1957-2020.

There are not enough earthquakes close to these stations for statistical conclusions, so there are no variations at close distances in the presented figures.

Conclusions

1. We have took into account that seismic data testify difference in the physical mechanisms of earthquakes at different depths; this gives grounds to assume as well the difference in the seismioionospheric effect of Eqs with different depths.

2. The presence of ionospheris anomalies of different sigh is shown for M6+ Eqs with H<35 км and 35<=H<70 km according to Tokyo station data for 1957-2020.

3. Accounting for possible differences in the nature of seismioionospheric effects allowed to increase essentially their statistical significance.

4. A method for identifying systematic anomalies against the background of strong random noise has been proposed and implemented.

5. Analysis of the nature of the identified statistically reliable seismioionospheric anomalies allows us to conclude that identified anomalies can be formed by the moderate (a few percents only) change in the background foF2 value; hence the question arises whether the previously reported anomalies of up to 40% are of a seismogenic nature or caused by other reasons.

Thank you for attention