Criticality features in ULF magnetic fields prior to the 2011 Tohoku earthquake

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Abstract: The criticality of ULF (Ultra-low-frequency) magnetic variations is investigated for the 2011 March 11 Tohoku earthquake (EQ) by natural time analysis. For this attempt, some ULF parameters were considered: (1) F_h (horizontal magnetic field), (2) F_z (vertical magnetic field), and (3) D_h (inverse of horizontal magnetic field). The first two parameters refer to the ULF radiation, while the last parameter refers to another ULF effect of ionospheric signature. Nighttime (L.T. = 3 am $\pm$ 2 hours) data at Kakioka (KAK) were used, and the power of each quantity at a particular frequency band of 0.03–0.05 Hz was averaged for nighttime hours. The analysis results indicate that F_h fulfilled all criticality conditions on March 3–5, 2011, and that the additional parameter, D_h reached also a criticality on March 6 or 7. In conclusion, criticality has reached in the pre-EQ fracture region a few days to one week before the main shock of the Tohoku EQ.

Keywords: earthquake (EQ), criticality, seismo-electromagnetics, natural time analysis, ULF magnetic fields, the 2011 Tohoku EQ

1. Introduction

Based on extensive studies during the last few decades it is generally accepted nowadays that electromagnetic phenomena appear prior to an earthquake (EQ).^{1)–4)} Using the amplitude data of VLF/LF (very low frequency/low frequency) transmitter signals propagating in the Earth-ionosphere waveguide during the 7-year observation, Hayakawa

et al. (2010)⁵⁾ established a significant statistical correlation between the perturbations in the lower ionosphere and EQs. Perturbations in the upper ionospheric F region observed as changes in f_oF_2 (critical frequency of F₂ layer) were also confirmed to be correlated with EQs based on long-term data.⁶⁾

Compared with these ionospheric phenomena, the number of reports is not so abundant for ULF (ultra low frequency) electromagnetic emissions, even though they were found promising for short-term EQ prediction.^{7)–10)} Seismogenic ULF electromagnetic waves are usually “emission or radiation” from the lithosphere as observed as intensification of ULF magnetic power.^{7)–10)} Whereas a new phenomenon in ULF magnetic field changes is vice versa, the depression (or a decrease) in the amplitude of ULF downgoing waves of magnetospheric origin.¹¹⁾

In addition to the above, there is another direction of signal processing based on the concept of critical evolution or self-organized criticality. There are a few possible methods along this line: One is fractal analysis,¹²⁾ and the other is “natural time” analysis introduced by Varotsos,⁴⁾ which has been applied to time series data of a point process like SES events.^{13),14)} This paper is an attempt to apply the natural time method to our ULF geomagnetic

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Fig. 1. Relative location of three ULF observations (KAK, MMB and KNY by black triangles) and most powerful ($M_w > 7$) and shallow (depth smaller than 100 km) EQs shown by circles which occurred from December 1, 2010 to May 31, 2011. Our target EQ took place on March 11, 2011. The center of the circle is the EQ epicenter and its color indicates the depth.

data observed in Japan, especially during a period of a few months before the 2011 Tohoku EQ.

2. ULF data and EQ information

The ULF data were obtained from the World Data Center (WDC) for Geomagnetism, Kyoto. The data from this WDC are provided in the format of IAGA (International Association of Geomagnetism and Aeronomy) 2000, in which the magnetic field is represented by four components: Horizontal (H), declination (D), vertical (Z), and total field (F).

We use ULF data from three magnetic observatories belonging to JMA (Japan Meteorological Agency): Memambetsu (MMB) (geographic coordinates: at $43^{\circ}54'36''\text{N}$, $144^{\circ}11'19''\text{E}$), Kakioka (KAK) (at $36^{\circ}13'56''\text{N}$, $140^{\circ}11'11''\text{E}$), and Kanoya (KNY) (at $31^{\circ}25'27''\text{N}$, $130^{\circ}52'48''\text{E}$) as shown by black diamonds in Fig. 1. The sampling frequency of magnetometers at these stations is 1 Hz. Positions and magnitudes of EQs with $M_w > 7$ and with depth

smaller than 100 km are also shown by circles in the same figure. We have used seismic data from the ANSS (Advanced National Seismic System) Worldwide Earthquake Catalog. The main shock of the Tohoku EQ took place at 14:46:18 JST (UTC+9h) on March 11, 2011 with its epicenter at the geographic coordinates ($38^{\circ}06'\text{N}$, $142^{\circ}52'\text{E}$) as shown in Fig. 1. The magnitude was $M_w = 9$ and the depth was about 20 km. This EQ is a very typical oceanic EQ of the plate subduction type. The distance of each magnetic observatory from the EQ epicenter is 640 km for MMB, 300 km for KAK, and 1,300 km for KNY, respectively.

3. Parameters of ULF magnetic fields to be analyzed

The concept of “natural time” is suitable for time series data of point processes, including seismicity and DC geoelectric potential. On the other hand, ULF variations are not a point process, but they are

continuous in nature, so that we have to think of what kind of ULF parameters should be used for the natural time analysis.

In the following, we present the results only from KAK which is closest to the EQ epicenter, because our preliminary studies indicated no significant unusual phenomena at other stations. We take, as the first step, the following procedure on ULF magnetic data to be used for the natural time analysis. To avoid industrial interference, we use ULF data only during nighttime (LT = 3 h a.m. $\pm$ 2 hours). After performing spectral analysis on the raw ULF data and choosing a particular frequency range of 0.03–0.05 Hz (for which we have observed clear effects in ULF¹⁵⁾), we average the squared amplitude during this nighttime interval to obtain one datum per day.¹⁵⁾

The following ULF parameters are generated to characterize the ULF magnetic data.

- (1) Horizontal magnetic field component, H component (power): $F_h = \langle H^2 \rangle$
- (2) Vertical magnetic field component, Z component (power): $F_z = \langle Z^2 \rangle$
- (3) Depression of horizontal magnetic field component: $D_h = 1/\langle H^2 \rangle$

The parameters F_h and F_z are considered indicators of ULF emission from the lithosphere. The third parameter D_h is the inverse of the horizontal magnetic field component so as to pay extensive attention to the changes in minimum values for investigating the depression of ULF waves (of magnetospheric origin) observed on the ground as the ionospheric signature.¹⁶⁾

Figure 2 illustrates temporal evolutions of some physical parameters: (from top to bottom) geomagnetic (D_{st} index) and seismic (K_{ls} index) activities, F_h , F_z , $P_{z/h}$, D_h , and ULF depression (δDep) as discussed in Ref. 15, all in the same frequency range of 0.03–0.05 Hz. The index K_{ls} is a function of EQ magnitude and epicentral distance.³⁾ As was already shown,^{15),17)} a significant peak in depression (δDep) on March 6 was observed as a precursor to the 2011 Tohoku EQ. Our glance at the temporal evolution of F_h , suggests an enhancement in the beginning (1st) of March, but we are not sure whether this is a real precursor to the EQ or not. This enhancement in F_h looks to be correlated with a decrease in D_{st} index. It will be shown that this kind of uncertainty can be investigated with the use of natural time analysis.

4. Natural time analysis method

The transformation of a time-series of “events” from the conventional time domain to natural time

Fig. 2. Top panel: Temporal evolution of geomagnetic (D_{st}) (unit is given on the right ordinate) and seismic (K_{ls}) (unit is given on the left ordinate) activities. 2nd and 3rd panels: root-mean-squares of the horizontal (F_h) and vertical (F_z) magnetic fields in the frequency band 0.03–0.05 Hz (in arbitrary unit (au)), and the 4th panel, $P_{z/h}$ (ratio of vertical and horizontal components). The 5th and bottom panels refer to the temporal evolutions of the inverse of the horizontal component (D_h) (in arbitrary unit (au)), and the normalized depression δDep as discussed in Ref. 15.

domain is performed by ignoring the time interval between events and retaining only its normalized order of occurrence. So the k th event corresponds to a natural time $\chi_k = k/N$, where N is the total number of successive events. The “energy” Q_k of each event is also retained. Then the time series (χ_k, Q_k) is studied. A system is considered to approach criticality when the parameter $\kappa_1 = \sum_{k=1}^N p_k \chi_k^2 - (\sum_{k=1}^N p_k \chi_k)^2 / (\sum_{k=1}^N p_k)$ ($p_k = Q_k / \sum_{n=1}^N Q_n$ is the energy of k th event normalized by the total energy) converges to $\kappa_1 = 0.070$ and at the same time both the entropy in natural time, $S_{nt} = \sum_{k=1}^N p_k \chi_k \ln \chi_k - (\sum_{k=1}^N p_k \chi_k) \ln (\sum_{k=1}^N p_k \chi_k)$ and the entropy under time reversal, S_{nt-} , satisfy the condition $S_{nt}, S_{nt-} < S_u = (\ln 2/2) - 1/4$, where S_u stands for the entropy of a “uniform” distribution in natural time.¹⁸⁾

The criticality is considered truly achieved when the following three conditions are also satisfied:¹⁸⁾ (i) The “average” distance $\langle D \rangle$ between the curves of normalized power spectra $\Pi(\phi)$ of the evolving seismicity and the theoretical estimation of $\Pi(\phi)$ for $\kappa_1 = 0.070$ is smaller than 10^{-2} , (ii) the parameter κ_1 approaches $\kappa_1 = 0.070$ “by descending from above”, and (iii) since the underlying process is expected to be self-similar, the time of criticality does not change by varying the magnitude threshold. It may be worth mentioning that these criticality conditions, including $\kappa_1 = 0.070$, were not derived theoretically but empirically from computing κ_1 values for well-known phenomena and actual data of seismicity in Greece.¹⁸⁾

5. Results of natural time analysis of ULF parameters

The natural time analysis starts from 5 January 2011, following the findings of Skordas and Sarlis (2014).¹⁹⁾ We consider each daily value which is above a certain threshold as an event. So in our ULF cases (F_h , F_z , and D_h), the “energy” of k th event Q_k is considered to be equal to each one of above quantities. Starting from 5 January 2011, all the parameters (κ_1 , S_{nt} , S_{nt-} , $\langle D \rangle$ in Section 4) are calculated for the time-series rescaled in the natural time domain each time a new event is added. Although the selection of thresholds is arbitrary, if criticality conditions are met in close dates for more than one of the considered threshold values, then this is considered to be an indication of the validity of performed analysis.

Results of natural time analysis for different ULF parameters are presented below.

(1) F_h (horizontal magnetic field)

Figure 3 illustrates an example of the natural time analysis results for F_h for a particular threshold. The four critical parameters κ_1 , S_{nt} , S_{nt-} and $\langle D \rangle$ are calculated each time a new event is included in the analysis, so their evolution is seen as a function of date of new event occurrence. We found that the process was self-similar because the time of criticality did not change by changing the threshold. Then F_h fulfilled all criticality conditions around the date of March 3, 4, or 5, 2011.

(2) F_z (vertical magnetic field)

The corresponding figures for F_z are not shown, because F_z did not exhibit any criticality condition.

(3) D_h (depression in horizontal magnetic field)

Figure 4 is again just one example of the results

Fig. 3. Natural time analysis of the ULF electromagnetic emission quantity F_h for the time period of 05 January through 11 March 2011: Variations of the natural time analysis parameters (κ_1 , S_{nt} , S_{nt-} , and $\langle D \rangle$) for a particular threshold.

Fig. 4. Natural time analysis of the ULF electromagnetic emission quantity D_h for the time period from 05 January to 11 March 2011: Variations of the natural time analysis parameters for a particular threshold.

of natural time analysis for the parameter D_h for a particular threshold. We confirmed that the date of criticality did not change by changing the threshold, and so it seems that D_h reaches a critical condition around March 6 or 7, 2011.

A question naturally arising is whether the analyzed parameters were observables of a process taking place in the Earth’s crust system or any other process that could influence magnetic field variations such as magnetic storms. In Fig. 2 we find two relatively small (-50 nT) storms on March 1 and March 11 (unfortunately this latter is masked by the plot of EQs in Fig. 2). These two magnetic storms occurred not on the same dates as the dates of

criticality indicated by the natural time analysis of ULF parameters (March 3, 4, or 5 for F_h , March 6, 7 for D_h).

6. Conclusion and discussion

This paper is the first attempt to analyze criticality in ULF magnetic fields by means of natural time method. The results of the natural time analysis can be summarized as follows.

- (1) Criticality reached a few days to one week prior to the main shock of the 2011 Tohoku EQ by fulfilling the criticality conditions for the two parameters F_h and D_h , but not for F_z .
- (2) These critical dates seem to have no association with geomagnetic activity.

First, we discuss the lithospheric aspect of the ULF parameters, F_h , and F_z . It is not clear why we have detected criticality only in F_h , but not in F_z . Tentatively, we consider as follows. The 2011 Tohoku EQ was the most powerful EQ ever recorded to have hit Japan, and Hirose *et al.* (2011)²⁰⁾ reported that the hypocentral region of this EQ is extended from offshore Iwate prefecture to offshore Ibaraki prefecture, with a length of 500 km and a width of 200 km. From the huge area of the rupture region, it may not be unreasonable to consider that the corresponding pre-fracture region is also very wide, even extending to our ULF observation point of KAK. Whatever the mechanism of electrification in the source region, dynamic processes in association with pre-EQ microfracture can lead to the generation of current systems.^{21),22)} Our finding of the criticality at KAK only in F_h , but not in F_z , may be explained by the relative position of the current source and observatory. When using the method as used in Kawate *et al.* (1998),²³⁾ we can infer that the source current, at least, responsible for the seismogenic ULF radiation observed at KAK, might have been located in an area relatively close to KAK, for example, offshore Ibaraki prefecture.

Next we move on to the ionospheric ULF phenomena. Criticality was observed on March 6 and 7 in the temporal evolution of critical parameters for D_h , which is in agreement with the conclusion of Schekotov *et al.* (2013).¹⁵⁾ They found a depression in ULF magnetic field intensity on the ground (as shown in the bottom panel of Fig. 2), which may be satisfactorily interpreted in terms of an enhanced absorption of downgoing Alfvén waves through the perturbed lower ionosphere.¹⁷⁾ It seems that the pre-EQ criticality has taken place in a wide area of the lithosphere, and the criticality is also recognized in

the lower ionosphere with a small time difference of one day or so. The area of lower ionospheric perturbation as sensed by the ULF magnetic field depression is found to be much wider^{15),17)} than such a localized area (radius less than 100 km) for the lithospheric ULF radiation observed at KAK. So the information on ionospheric perturbations derived from D_h is likely to reflect the criticality taking place on March 6 and 7 in the lithosphere over a wider area of the rupture region in the Pacific ocean. The difference in criticality dates for F_h and D_h is probably due to slightly different dates for criticality at a relatively localized region near KAK and at a much wider pre-EQ fracture region.

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