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Evaluation of ULF electromagnetic phenomena associated with the 2000 Izu Islands earthquake swarm by wavelet transform analysis

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Abstract. There have been many reports on ULF electromagnetic phenomena associated with the 2000 Izu Islands earthquake swarm. In this study, seismo-magnetic anomalies are presented by examining energy variations of signatures at the periods around 100 s. Geomagnetic data observed at three stations in Izu Peninsula from 1 January 2000 to 30 April 2001 have been analyzed and wavelet transform has been performed. In order to indentify anomalous changes from ionosphere disturbances, Kakioka station has been chosen as a reference station, and the similar data analysis has been performed. The results suggest that the unusual energy enhancement of the Z component, which only appears in Izu Peninsula from late June until early November 2000, might possibly be one of electromagnetic phenomena associated with the 2000 Izu Islands earthquake swarm.

1 Introduction

Earthquakes are one of the most destructive of all natural hazards, and it has long been a dream of scientists to achieve effective prediction. The detection of electromagnetic perturbations prior to fault ruptures or volcanic eruptions has often been proposed as a simple and effective method for monitoring crustal activities. And electromagnetic phenomena have been considered promising candidates for short-term earthquake prediction. So far, a lot of evidence of seismo-electromagnetic precursory signatures in a wide frequency range from DC to VHF has been reported (e.g., Johnston, 1997; Hayakawa et al., 2008). Meanwhile,



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abundant indoor/outdoor experiments and numerical simulations (Molchanov and Hayakawa, 1995; Huang and Ikeya, 1998; Huang, 2002, 2005; Huang and Lin, 2010) have confirmed the existence of this seismo-electromagnetic phenomenon.

Because of skin depth, passive ground-based observation of ULF (ultra low frequency) geomagnetic signatures is considered to be the most promising method for seismomagnetic phenomena study. In order to verify electromagnetic phenomena preceding large earthquakes, a sensitive geomagnetic network has been installed in Japan (Hattori et al., 2004a) and plenty of data associated with moderate-large earthquakes have been accumulated.

So far, there have been many reports on the ULF electromagnetic phenomena associated with the 2000 Izu Islands earthquake swarm. Different kinds of methodologies have been performed, such as principal component analysis (PCA) (Uyeda et al., 2002; Hattori et al., 2004b), fractal analysis (Gotoh et al., 2004; Telesca et al., 2007, 2008), polarization analysis (Ismaguilov et al., 2001, 2003; Kotsarenko et al., 2005) and direction-finding analysis (Ismaguilov et al., 2003; Kopytenko et al., 2006). In previous studies, the most significant results were found in H (N-S) component by PCA and fractal analysis. In addition, we have found that there is a remarkable enhancement of energy in the Z (vertical) component at the period around 100 s during the earthquake swarm using wavelet transform. After comparing the results with those at a reference station and geomagnetic activities, it is highly suggested that the anomalous enhancement of energy might be one of seismomagnetic phenomena associated with the 2000 Izu Islands earthquake swarm.



Fig. 1. Spatial distribution of geomagnetic stations and earthquake epicenters. Blue triangles indicate ULF magnetic observations in Izu Peninsula and reference station; black stars present the epicenters of earthquakes with magnitude greater than 6; red circles give the locations of earthquakes $4.0 \le M \le 6.0$.

No.	Date	Latitude	Longitude	Magnitude	Depth	Epicentral distance
				(JMA)	(km)	(km)
(1)	1 July 2000	34.11° N	139.12° E	6.5	16	88
(2)	8 July 2000	34.13° N	139.14° E	6.1	15	88
(3)	15 July 2000	34.25° N	139.15° E	6.3	10	74
(4)	30 July 2000	34.02° N	139.24° E	6.0	11	102
(5)	18 August 2000	34.12° N	139.14° E	6.1	12	88

Table 1. Parameters of earthquakes ($M \ge 6.0$) during the 2000 Izu Islands earthquake swam.

2 Seismic activities and geomagnetic data acquisition

The first alarm of the approaching eruption of the Oyama volcano, Miyakejima Island (34.09° N, 139.51° E) came from the Japan Meteorological Agency on 26 June based on the increased occurrences of small earthquakes under the island. Next morning, there was an indication of undersea eruption several kilometers west of the island, and the seismic swarm activity started almost simultaneously. There were five large earthquakes ($M \ge 6$) during this activity which occurred on 1, 8, 15, 30 July, and 18 August 2000 with magnitude of M6.5, 6.1, 6.3, 6.0 and 6.1, respectively. Details are given in Table 1 (based on Catalog issued by the Japan Meteorological Agency).

In this study, we analyze the ULF geomagnetic data observed at three stations closely distributed on the Izu Peninsula (Seikoshi (SKS) (34.85° N, 138.82° E), Mochikoshi (MCK) (34.89° N, 138.86° E), and Kamo (KAM) (34.86° N, 138.83° E)). The duration of the data is from 1 January 2000 to 30 April 2001. The distances between the geomagnetic stations and hypocenters ($M \ge 6.0$) are about 80 to 100 km. Figure 1 shows the relative location of magnetometers and earthquake epicenters ($M \ge 4.0$). The inter sensor distance is about 5 km, and Torsion type magnetometers with three components are in operation (see details in Hattori et al., 2004b). The original sampling rates are 50 Hz for SKS and MCK stations; 12.5 Hz for KAM station. Here we

re-sample the data to 1 Hz. As a reference, 1 Hz sampling geomagnetic data of Kakioka (KAK) station operated by the Japan Meteorological Agency was investigated.

3 Wavelet analysis method

Fourier analysis is the most popular and widely-used method for signal analysis in frequency domain. However, it is poorly suited for problems concerned with detection of low-magnitude short-lived events, especially in the case of impulses. On the contrary, wavelet analysis provides relevant means for such cases by introducing not only wavelet functions but also scale (window) parameters. Therefore, wavelet analysis is now a powerful tool in numerous areas, particularly for signal analysis (Alperovich et al., 2003). The basic formula for wavelet transform is as shown

$$WT_x(a,\tau) = \frac{1}{\sqrt{a}} \int_{-\infty}^{+\infty} x(t) \psi^*\left(\frac{t-\tau}{a}\right) dt \quad (a>0)$$
(1)

where *a* is scale parameter; τ is the localized time. *x* and ψ are the signals and basic wavelet, respectively. * indicates the complex conjugate, and WT presents the wavelet transform result (wavelet coefficient). To reconstruct the time series data, inverse transformation is given as follows:

$$x(t) = \frac{1}{C_{\psi}} \int_{0}^{+\infty} \frac{da}{a^{2}} \int_{-\infty}^{+\infty} WT_{x}(a,\tau) \frac{1}{\sqrt{a}} \psi\left(\frac{t-\tau}{a}\right) dt$$
$$C_{\psi} = \int_{R} \frac{|\psi(\omega)|^{2}}{|\omega|} d\omega < \infty$$
(2)

In the wavelet analysis, the signals studied are expanded into a unit of waveforms well localized both in time and frequency domains, which means we can get detailed (relatively) information on signals in the time domain and frequency domain simultaneously.

In this paper, we perform discrete wavelet transform and decompose the original signature into six levels. The central frequency (F_a) of signals in each level is given as

$$F_{\rm a} = \frac{F_{\rm c}}{a\Delta} \tag{3}$$

where F_c is the frequency of a basic wavelet; *a* is the scale of the level. Δ is sampling rate of the original data.

After evaluating different kinds of wavelets, we adopted Daubechies 5 (db5) as the mother wavelet for data analysis. Moreover, it has also proved to be effective in the previous study (Jach et al., 2006). According to Eq. (3), for the db5 wavelet, the central frequency of signals in the sixth level is 0.01 Hz. Figure 2 gives scale function (a) and wavelet function (b) of the db5 mother wavelet. Figure 2c presents an example of wavelet transform results in the sixth level.



Fig. 2. Parameters of the db5 wavelet and an example of the results. (a) Scale function; (b) wavelet function; (c) wavelet transform results of three hours of data ($15:00 \sim 18:00$ UTC) observed at SKS station on 20 November 2000.

4 Results and discussion

4.1 Variation of energy

In this section the temporal variations of energy at each station on the Izu Peninsula have been described. Because there is much less noise at night (Hattori et al., 2004a), we used daily only the data from $00:00 \sim 03:00$ LT ($15:00 \sim 18:00$ UTC) for computation. Wavelet analysis was applied to three hours of data to detect the earthquake-related signals at a frequency of around 0.01 Hz, and the energy of the signatures was calculated for each day. Figures 3 and 4 illustrate the temporal variations of energy of H and Z components at the stations on the Izu Peninsula, respectively.

In both figures, the energy at each station is quite similar. Especially for the Z component, it was found that the energy at all three stations on the Izu peninsula begins to increase from June 2000 onwards, and this remarkable enhancement lasts until November. However, in the H component (Fig. 3), a similar variation could not be detected. In order to clarify whether this unusual behavior is local or global, information at the remote reference station and geomagnetic activity index should be investigated (Hattori et al., 2004a).

4.2 Discussion

In this section possible reasons of the enhancement of energy at the stations on the Izu Peninsula will be discussed. In general, ULF geomagnetic data observed on the ground are a superposition of several kinds of signatures. The most intense one is geomagnetic pulsations, which are considered



Fig. 3. Temporal variation of energy of the H component. From the top panel to bottom are the results at the SKS, KAM and MCK stations, respectively. The blue solid line gives the daily value of the energy, and the red broken line presents the five days running mean.



Fig. 4. Temporal variation of energy of the Z component. From the top panel to bottom are the results at SKS, KAM and MCK station, respectively. The blue solid line gives the daily value of the energy, and the red broken line presents the five days running mean.

to be global. The next one is artificial noise due to DC-driven trains, factories and so on. The third one is earthquake-related signals, which can only be detected in the region close to the focal zone (Hattori et al., 2004a).

In our computations, we only use the mid-night data when the human activity is very low, so the anomalous changes are not likely due to artificial noise. To eliminate the influence of global pulsations, we chose the KAK observatory as a reference station and investigated its energy variation. Figure 5 illustrates the temporal variations of energy at the SKS station on the Izu Peninsula (a) and the reference station (b). Because the variations of the three stations in Izu area are quite similar, we only show the variation at SKS station here. Figure 5c gives the ap index during $15:00 \sim 18:00$ UTC;



Fig. 5. Temporal variation of energy at SKS station and a reference station (KAK). (a) Energy at SKS station; (b) energy at KAK station; (c) ap index (15:00 ~ 18:00 UTC); (d) Es parameter. The blue solid line gives the daily value, and the red broken line presents the five days running mean. The vertical dashed lines indicate the occurrence time of $M \ge 6.0$ earthquakes.

Fig. 5d shows Es index, which is the daily sum of the local earthquake energy obtained from the following formula (Hattori et al., 2006)

$$Es = \sum_{1 \text{ day}} \frac{10^{4.8+1.5M}}{r^2}$$
(4)

where M and r indicate the magnitude of earthquake and hypocenter distance from the observation array on the Izu Peninsula, respectively.

Figure 5a shows that there is a clear enhancement of the energy at SKS station from June to November. As for a statistical check, the five days running mean exceeds the mean plus 2σ several times during the earthquake swarm. However, the energy at KAK station and ap index are sometimes also relatively very high. So it is not suitable to discuss these anomalies, whether related to the earthquake or not during these periods.

But when focusing on the region marked by shadows, it is quite sure that the energy enhancement is local, because both the ap index and results at the reference station are low. Meanwhile, the energy just reaches the maximum several days prior to the first (second) and forth large earthquakes $(M \ge 6.0)$. The results for the other two large earthquakes were polluted by ionospheric disturbances.

5 Conclusions

The ULF geomagnetic data observed on the Izu Peninsula have been investigated by the wavelet analysis method to detect any possible anomalous changes related to the 2000 Izu Islands earthquake swarm. It was found that the energy of the Z component exhibits a remarkable increase during the intensive seismic activities, while no similar behavior exists in the H component. After comparing the results with those at the reference station and ap index, we conclude that the unusual behavior does not likely result from global ionospheric disturbances; this pertains especially to the results marked by shadows. These facts highly suggest that the unusual enhanced energy of the signatures at the frequency around 0.01 Hz observed on the Izu Peninsula would be one of phenomena associated with the 2000 Izu Islands earthquake swarm.

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