

The signature of the 2011 Tohoku mega earthquake on the geomagnetic field measurements in Japan

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Abstract On 11 March 2011 at 05:46:23 UTC, a mega earthquake (EQ) with magnitude (M_w) 9.0 [The 2011 Tohoku Earthquake] occurred at a depth of about 24 km near the East coast of Honshu Island, Japan as a result of a thrust faulting on or near the subduction plate boundary between the Pacific and North American plates. Geomagnetic data from MAGDAS and Geospatial Information Authority of Japan (GSI) networks have been analyzed to examine the signature of the 2011 Tohoku earthquake on the geomagnetic field measurements in Japan. Results of data analysis indicate about 5 nT increase in the total geomagnetic field intensity in the vicinity of the epicenter of 2011 Tohoku EQ compared with other reference stations. Moreover, the annual range of the Z-component daily variations tends to decrease near the epicenter before the occurrence of the Tohoku EQ. Concerning the ULF emissions; the Pc 3 amplitude ratio ($ZPc3/HPc3$) near the epicenter at the Onagawa [ONW] station showed a good correlation with other remote reference stations before the Tohoku EQ but it started to decrease with no correlation to other stations a few weeks before the 2011 Tohoku EQ. On the other hand, the Pc 3 amplitude ratio at ONW station showed a clear anti-correlation compared with reference stations after the 2011 Tohoku EQ.

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1. Introduction

The lithosphere is broken up into a number of pieces called tectonic plates and most of the earthquakes occur at the boundaries of these plates. Earthquakes can cause great damages as well as loss of many lives. Most of earthquake-related deaths are caused by the collapse of structures such as buildings and bridges during the shaking of earthquakes. Therefore, finding a way to predict earthquakes or constructing a warning system for earthquakes can be helpful for reducing the earthquake damages and mortality rate. Generally, there is no direct

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way to predict earthquakes depending on the seismicity. Thus, it is very important to look for an indirect way by finding some crustal physical parameters that can show some anomalous behavior in association with earthquakes. In this case, the variations in these physical parameters can be used as earthquake precursors. The anomalous variations in the geomagnetic field can be one of the precursors (Vere-Jones, 1995).

Several sources can cause variations in the total geomagnetic field measurable on the ground. These variations can be classified as either external or internal variations with respect to the earth's surface. The solar wind, magnetosphere and ionosphere are the main sources of the external geomagnetic variations, while the internal geomagnetic variations are linked with the tectonic processes and generally related to the induced and remanent magnetization within the lithospheric crust (Merrill et al., 1996; Manda and Purucker, 2005). The idea of monitoring the tectonic activity using the stress-induced geomagnetic variations was proposed first by Wilson (1922). The experimental works have shown that the variation in stress field can produce changes in the rock's magnetic properties (Nagata, 1969; Revol et al., 1977; Kapička et al., 1997). Therefore, the concept of peizomagnetism has been proposed to explain the generation of anomalous geomagnetic field variation related to the tectonic processes (Stacey, 1964; Nagata, 1969, 1970; Stacey and Johnston, 1972).

Many studies have been done to examine the interrelationship between the geomagnetic field variations and the seismic activities in Japan. The results indicate a possible association between anomalous geomagnetic field variations and a number of earthquakes (Rikitake and Yokoyama, 1955; Yamazaki and Rikitake, 1970; Mogi, 1985; Hattori et al., 2002; Hattori, 2004; Nishida et al., 2007; Hayakawa et al., 2007 and Yumoto et al., 2009 among many others). Thus, precursory phenomena associated with a number of earthquakes have been reported. However, several studies have reported the interrelation between anomalous changes of the geomagnetic field and earthquakes, discussions and arguments are still arising about the signature and influence of earthquakes on the geomagnetic field measurements. Since Japan is covered by a network of well-distributed geomagnetic stations, data from MAGDAS network and the Geospatial Information Authority of Japan (GSI) have been analyzed to examine the occurrence of any anomalous geomagnetic field variation related to the 2011 Tohoku earthquake.

2. The 2011 Tohoku earthquake

Japan is located in a seismically active zone (the so-called Pacific Ring of Fire) at the Eastern edge of the Asian continental plate. Therefore, Japan is particularly prone to both earthquake and volcanic activities, sometimes to a devastating effect (as in case of the 2011 Tohoku EQ) because it is located at a point on the Earth's surface where a number of tectonic plates interact with each other. The Japanese Islands lie at the junction of four major tectonic plates; which are the Pacific plate, the Philippine Sea plate, the North American plate and the Eurasian plate as shown in Fig. 1 (Wei and Seno, 1998).

The 2011 Tohoku earthquake, also known as the Great East Japan Earthquake, struck the eastern coast of the Honshu Island, Japan with magnitude (M_w) 9.0 (after the Japan Meteorological Agency [JMA]). This earthquake was an undersea

mega thrust earthquake that occurred at 05:46:23 UTC on Friday, 11 March 2011, with the hypocenter (38.322°N , 142.369°E) at a depth of approximately 24 km. It was the most powerful known earthquake to have hit Japan. The earthquake triggered extremely destructive tsunami waves of up to 38.9 meters that struck Japan (after JMA, GSI and United States Geological Survey [USGS]).

3. Geomagnetic data

The geomagnetic data used in the present study are provided by MAGDAS and GSI networks. The distribution of the geomagnetic stations is shown in Fig. 1. MAGDAS Project (PI: Prof. K. Yumoto) is recently considered the world's largest array of magnetometers, since over 60 MAGDAS real-time magnetometers are installed all over the world. The MAGDAS magnetometer is a ring core-type fluxgate magnetometer that can measure even small-amplitude geomagnetic fluctuations. It has three sensors along three orthogonal directions and measures the three components of the geomagnetic field [North–South component (H), the East–West component (D) and the Vertical component (Z)]. The sampling frequency is 16 Hz, but the instrument makes on-board calculations of the 1-s arithmetic averages of the 16-Hz data. The acquired geomagnetic data are transferred from the overseas stations to the International Center of Space Weather Science and Education (ICSWSE) at Kyushu University-formerly, Space Environment Research Center (SERC)-Japan in near real-time. Moreover, the same data are stored in a compact flash memory card in situ (Yumoto et al., 2006, 2007). Data from MAGDAS stations at Ashibetsu (ASB), Tohno (TNO), Onagawa (ONW) and Kuju (KUJ) in Japan have been used in the present study. In addition, the Legazpi (LGZ) MAGDAS station in Philippines has been used as a remote reference. The geomagnetic data from GSI stations were recorded using fluxgate and proton magnetometers. The sampling rate of the fluxgate magnetometer is one minute and the absolute observations are carried out once a year for the baseline determination. The recorded data at each station are transmitted to GSI through the public telephone line (Tanabe, 1997). The GSI stations used in the present study are Akaigawa (AKA), Yokohama (YOK), Haramachi (HAR), Shika (SIK), Otaki (OTA), Hagiwara (HAG), Yoshiwa (YOS), Totsukawa (TTK), Muroto (MUR) and Kuju (KUJ). The original data obtained from GSI stations are one minute data of the total magnetic field intensity (F), declination (D), horizontal (H) and vertical (Z) components. The GSI data format was modified by Dr. T. Uozumi at ICSWSE, the Kyushu University to match with the data format provided by MAGDAS network, in which (H) is referring to the North–South component, (D) is referring to the East–West component and (Z) is referring to the Vertical component.

4. Results of data analysis and discussion

The availability and quality of the geomagnetic data are very important factors in the study of anomalous geomagnetic variations related to seismic activities. In addition, it is commonly accepted that a network of stations are necessary for observing and extracting the precursory phenomena or anomalous geomagnetic variations associate with earthquakes. In the present

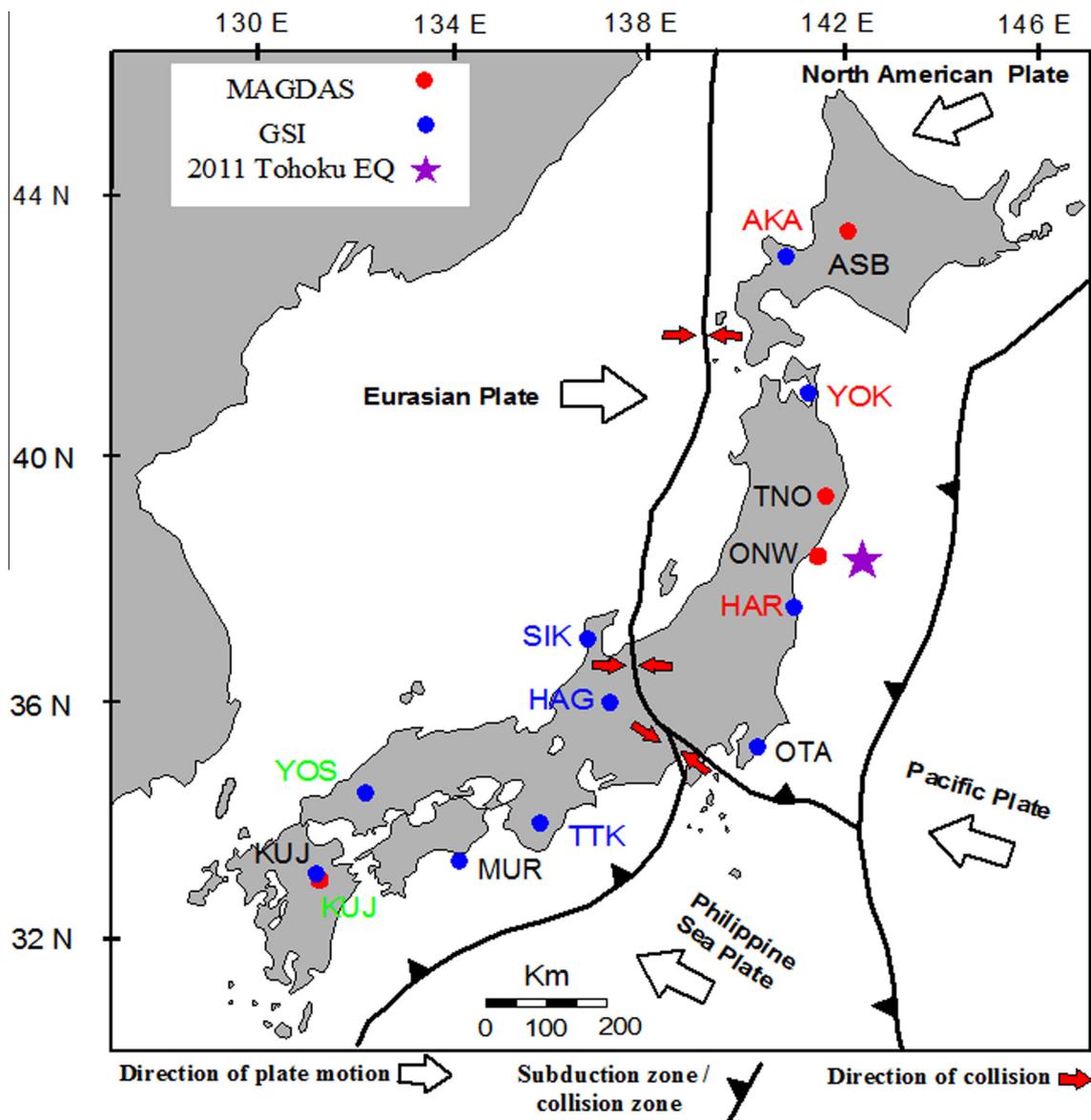


Fig. 1 The plate tectonic boundaries and the tectonic elements around Japan. Also, the figure shows the distribution of the geomagnetic stations as well as the epicenter of the 2011 Tohoku earthquake.

study, the availability of geomagnetic data gives us a good opportunity to study the anomalous geomagnetic variations that may be related to the 2011 Tohoku EQ. The comparison between the geomagnetic data in the vicinity of the epicenter and those recorded at remote reference stations (outside the epicenter) is considered as an effective technique to detect the anomalous variation of a lithospheric origin.

4.1. Long-term geomagnetic field variations in Japan between 2001 and 2011

One-minute geomagnetic data recorded by GSI network are averaged to get the daily average values of the total magnetic field intensity (F) and H-, D-, and Z-components during the period from January 2001 to September 2011. The daily average values during that period of time are plotted to discriminate the existence of any long-term geomagnetic variations as shown in Fig. 2. The total intensity (F) shows

a decreasing trend up to 2005. After that, (F) starts to show inconstant increasing patterns along all stations. The increasing rates are not uniform at different geographic locations. The Northern stations show greater increasing rate than those in the Southern stations, see Fig. 2a. The H-, D-components are also found to show inconstant decreasing pattern with time, Fig. 2b and c. On the other hand, the Z-component is almost constant up to 2005. After 2005, the Z-component shows a clear different behavior. The Z-component starts to increase gradually but with a different increasing rate at the Northern and Southern parts of Japan as shown in Fig. 2d.

The main geomagnetic field of the Earth is generated by convective motions in the fluid outer core and it can be approximated by a geocentric axial dipole (Merrill et al., 1996). This field represents over 97% of the total field observed at the Earth's surface. The dipole moment of the Earth has been steadily decreasing since systematic intensity

measurements began in the 1840's. The variations of the total geomagnetic field have a wide range, from seconds or minutes to millions of years. Long-term variations are mainly due to the dynamo process and they are known as secular variations (Dormy and Manda, 2005). The anomalous behavior of the total geomagnetic field (from decreasing to increasing trend after and before 2005) may be related to a mantle anomaly

beneath Japan and/or changes in the dynamo process in the outer core. While, inconstant changing rate (increasing or decreasing) of the F, H, D, and Z-components at different locations may be related to different tectonic settings (different tectonic plates) at the Northern and Southern parts of Japan as shown in Fig. 1 (different changing rates represented by different colors, red, blue and green).

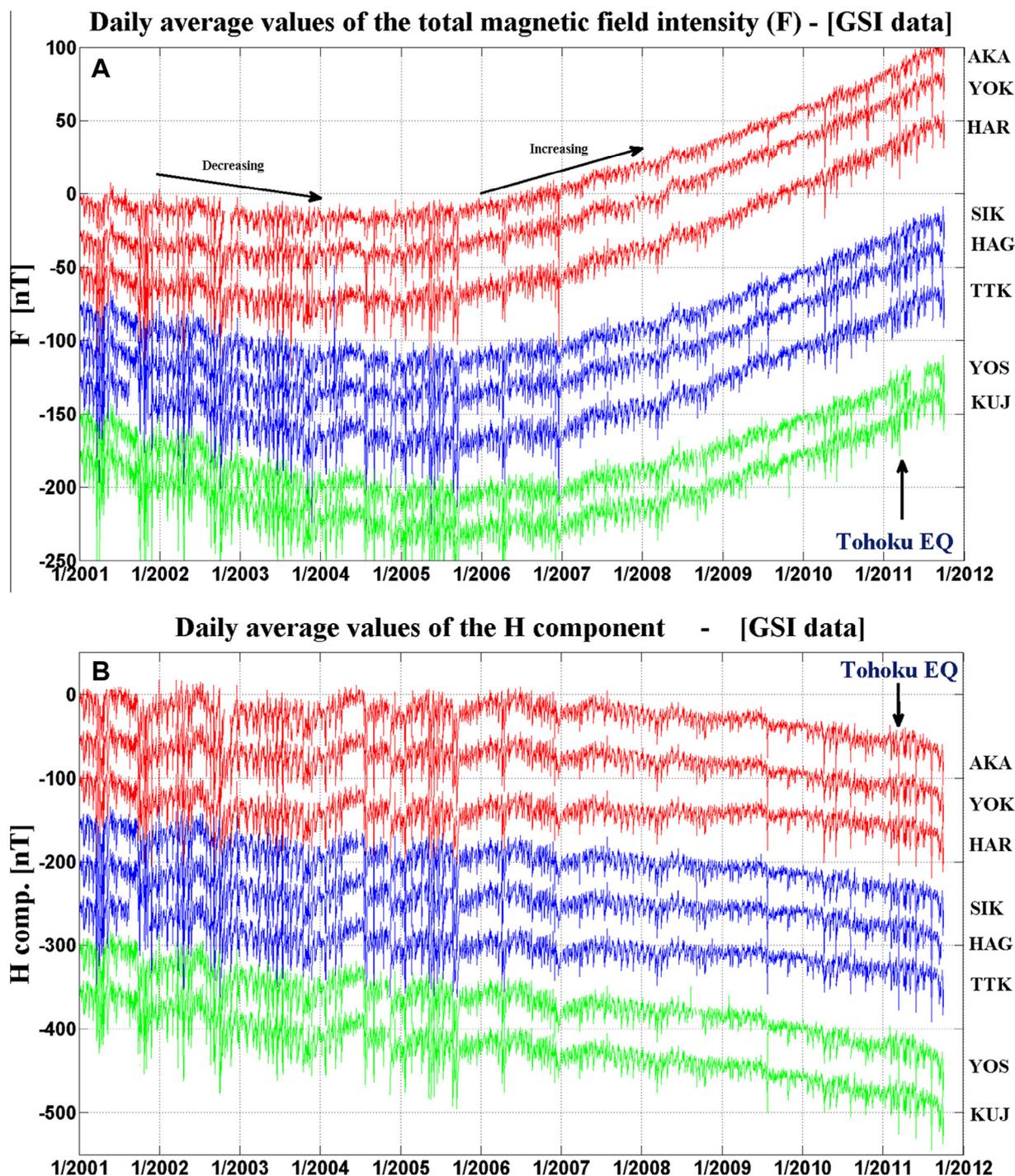


Fig. 2 Comparison of daily averaged values of the total magnetic field (F) and the H-, D- and Z-components in [nT] over 2001–2011 provided by GSI network. Different colors indicate different changing rates at these components. The stations can be separated into 3 groups with different changing rates (represents by red, blue and green colors). At the starting point (2001); all stations had a fixed and constant spacing on the vertical axis.

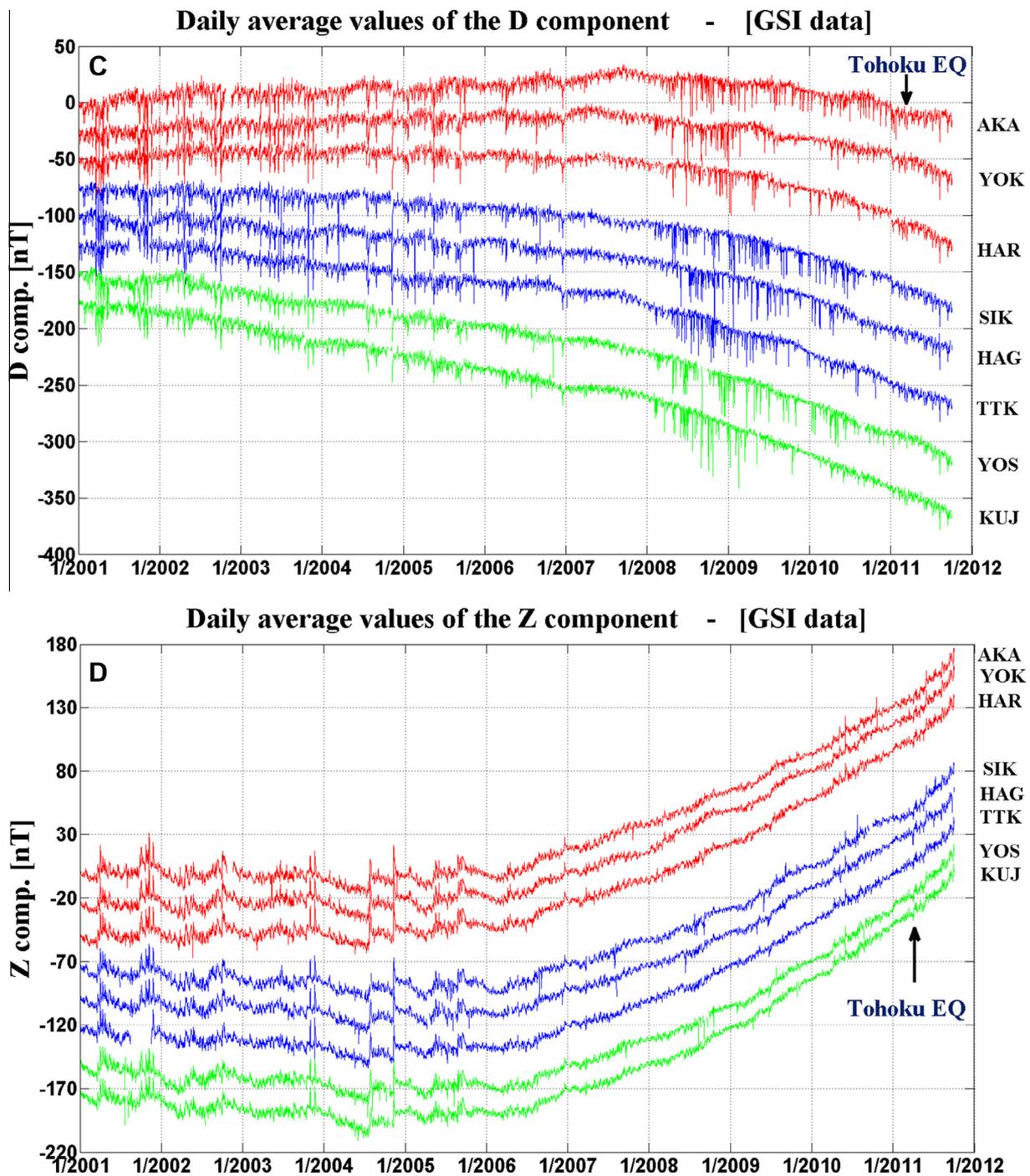


Fig. 2 (continued)

In addition to the core-origin main field, there is another source that contributes to the total magnetic field measurable on the ground. This source is the crustal field, originating in the Earth's crust from induced and remanent magnetization within the lithospheric crust. The change in the crustal stress conditions (stress accumulations) before the seismic activity can cause variations in rock magnetic properties such as the magnetic susceptibility, conductivity along with the induced and remanent magnetization. Thus, local crustal geomagnetic anomalies are expected to occur in the vicinity of the epicenter

due to the changes in the crustal stress field (tectonomagnetic phenomena). However, the detection of tectonomagnetic anomalies is a difficult issue because they are generally smaller than the variation of the main field (external variations). An effective way to extract the tectonomagnetic effect is to take the difference between the geomagnetic fields observed simultaneously at a network of stations (Stacey and Westcott, 1965; Yamazaki and Rikitake, 1970; Honkura, 1981). Since the main field variation is approximately uniform in a small area (Gough, 1973), the difference of the total fields between

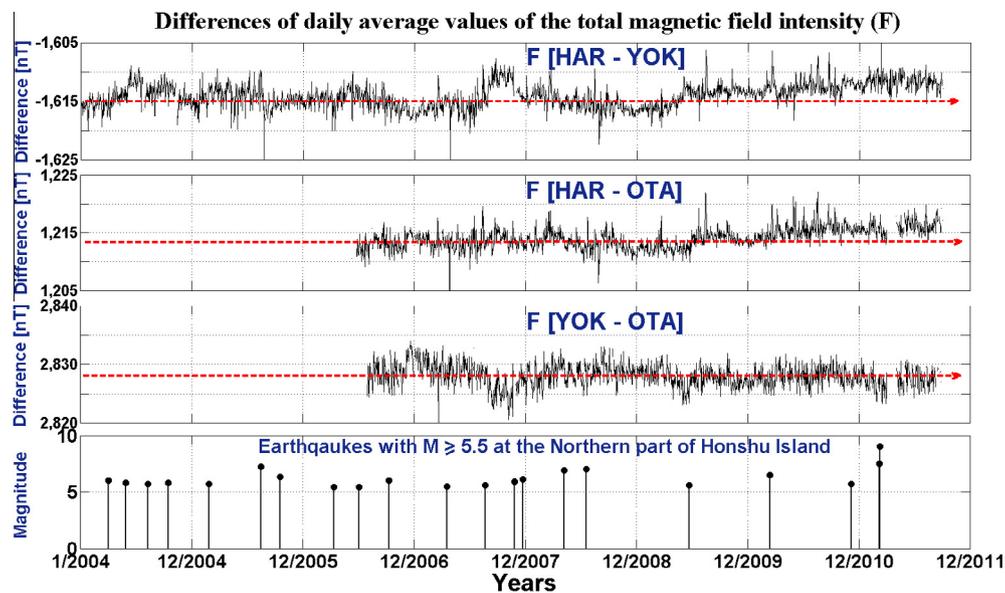


Fig. 3 The differences (Δ) of the total geomagnetic field recorded at the YOK, HAR and OTA stations during the period from January 2004 to September 2011. The lower panel represents the earthquakes that occurred near the YOK, HAR and OTA stations with a magnitude ≥ 5.5 . After the main shock of the 2011 Tohoku earthquake, many aftershocks with a magnitude greater than 5.5 occurred in that region, here only one example is shown (main shock and one aftershock). The red dashed arrows can be used as a reference to clarify the increase in the total magnetic field.

geomagnetic stations is expected to contain only the tectonomagnetic phenomena.

To detect any tectonomagnetic variations, we calculate the differences of the total geomagnetic fields recorded at HAR station; which is located near the epicenter of the 2011 EQ and two reference stations; the YOK and OTA stations (ΔF [HAR-YOK] and ΔF [HAR-OTA]) as shown in Fig. 3. The HAR station is located about 140 km away from the epicenter. Moreover, the difference between the two reference stations YOK and OTA (ΔF [YOK-OTA]) is calculated and plotted as shown in the third panel in Fig. 3. The results indicate an increase in the total magnetic field intensity at the HAR station in the vicinity of the epicenter. About 5 nT increase in the total magnetic field is observed at HAR station starting from 2009. On the other hand, the difference between YOK and OTA does not show such an increase. In addition, we plotted the earthquakes (magnitude ≥ 5.5) that occurred at a distance less than 100 km from each of the three stations. As we can see in Fig. 3, there is a good correlation between the occurrence of the earthquakes and the fluctuations in the difference of the total magnetic field at the three stations.

The conclusion that can be obtained from Fig. 3 is that the observed increase in (F) at HAR station can be linked with the variation in the crustal stress field and the underground conductivity near the epicenter of the 2011 Tohoku EQ (signature of the tectonic processes).

4.2. Changes in annual range of daily geomagnetic variations in Japan

The daily geomagnetic field variation is a regular small variation with a fundamental period of 24 h and it can be observed clearly during periods of low solar activity. Therefore, it is often

referred to as the Solar quiet (Sq) variation. The daily variations observed at the ground surface are mainly generated in the Earth's ionosphere by the dayside electric currents (Campbell, 1989). Thus, these variations are mainly local time phenomena. In addition to the primary source, currents induced in the solid Earth by the time-varying magnetic field of ionospheric origin are considered as a secondary source that contributes to the daily variations (Kuvshinov and Utada, 2010).

The hourly averaged values of the geomagnetic components are used to calculate the range of daily variation. Comparisons of the H-, D- and Z-component's daily variation range have been done in the period between January 2001 and September 2011 to examine any anomalous changes in the amplitude of daily variations. Some considerations can be made from these comparisons, by comparing the same component, a clear seasonal dependence of the daily variation amplitude range is observed. In addition, the trend of daily variation range tends to decrease with time; which may be correlated with the solar cycle activity.

After examining the annual range of daily variations for the H-, D-, and Z-components between 2001 and 2010 as shown in Fig. 4a and b, we find that the annual range of the Z-component daily variations tends to decrease near the epicenter (at ONW and HAR stations) as shown in Table 1. To confirm this observation, we examined the ratio of the annual range of daily variations for the three geomagnetic components at 2010 and 2001 (H [2010/2001], D [2010/2001], and Z [2010/2001]). The results indicate a clear depletion in the Z-component ratio at the ONW and HAR stations; which means that the annual range of Z-component became much smaller during 2010 at the ONW and HAR stations compared with other stations (see Table 1). Moreover, the annual range ratio (Z/H) of the daily variations has been calculated along a meridional array

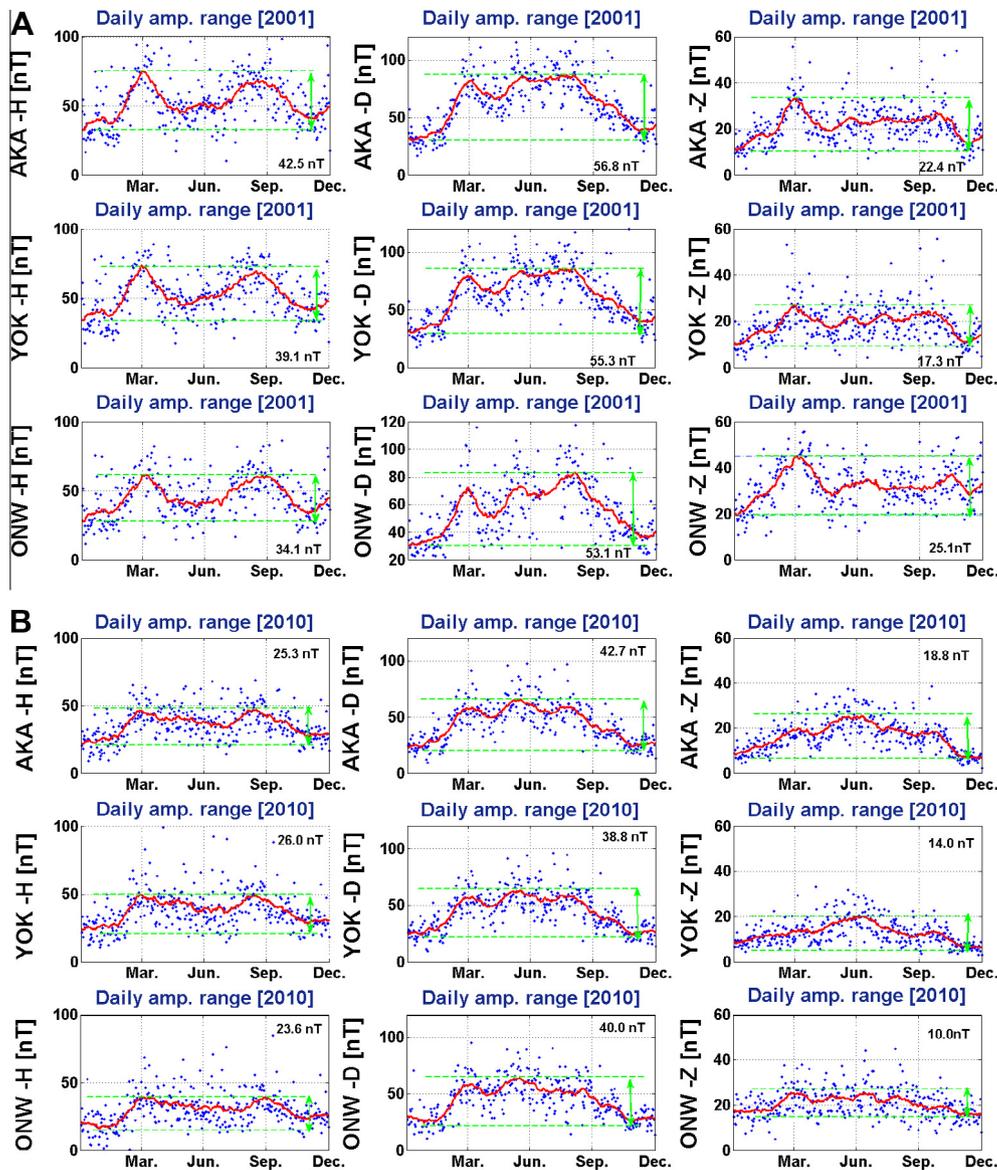


Fig. 4 The annual range of daily variations for the H-, D- and Z-components during 2001 and 2010 at three geomagnetic stations. Blue dots represent the range of daily variations, while the red lines represent 1 month running average.

Table 1 The annual range of the daily variations during 2001 and 2010.

Station	H (2001)	H (2010)	Ratio	D (2001)	D (2010)	Ratio	Z (2001)	Z (2010)	Ratio
AKA	42.5	25.3	59.5	56.8	42.7	75.2	22.4	18.8	83.9
YOK	39.1	26.0	66.5	55.3	38.8	70.2	17.3	14.0	80.9
ONW	34.1	23.6	69.2	53.1	40.0	75.3	25.1	10.0	39.8
HAR	33.2	18.6	56.0	56.6	37.1	65.6	19.5	9.1	46.7
SIK	35.2	19.6	55.7	57.8	41.0	70.9	23.2	18.1	78.0
HAG	33.3	18.9	56.7	58.8	39.0	66.3	22.0	15.1	68.6
YOS	34.4	17.4	50.6	61.5	41.3	67.2	25.1	17.0	67.7
TTK	30.1	18.0	59.8	60.6	38.8	64.0	22.2	12.7	57.2
KUJ	34.1	18.4	53.9	61.2	43.3	70.7	23.2	14.3	61.6

Note: Ratio =annual range of daily variations during 2010 / 2001

of stations from AKA to KUJ between 2001 and 2010 as shown in Fig. 5. The results indicate a clear change in the ratio during 2010 compared with the previous years. So, the

observed anomaly can be associated with the anomalous distribution of underground conductivity near the epicenter of 2011 Tohoku EQ.

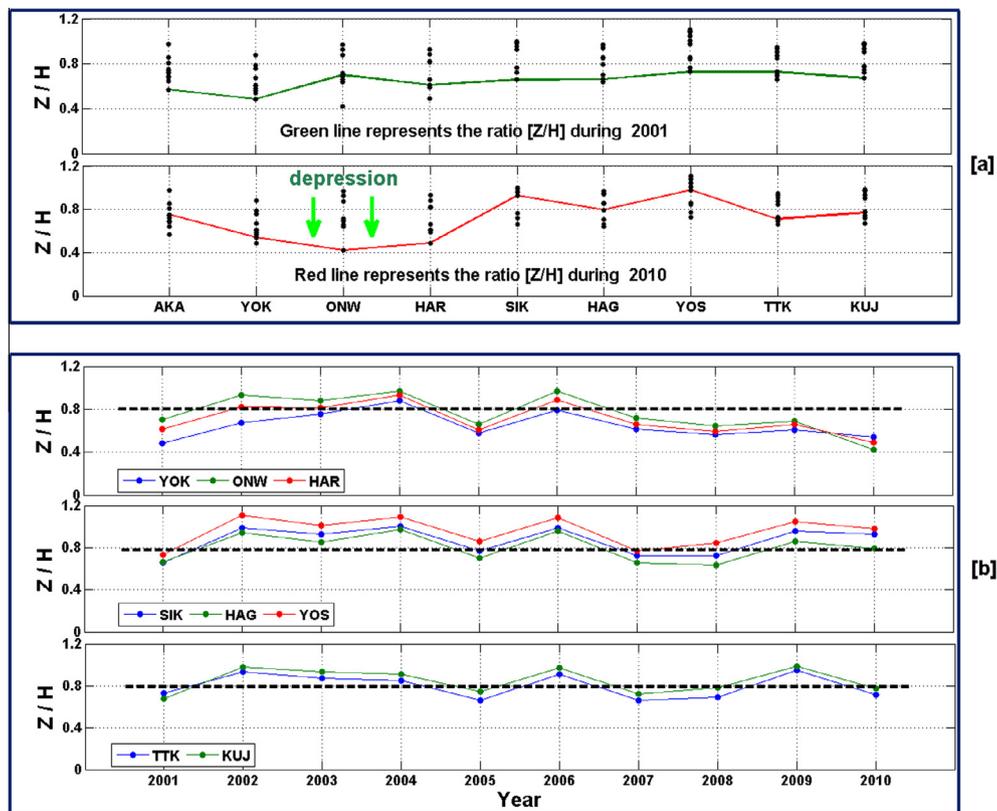


Fig. 5 (a) The ratio (Z/H) of the annual range of daily variations along a meridional array between 2001 and 2010 (2001 and 2010 are represented by solid green and red curves respectively). During 2010, a clear depletion of the ratio (Z/H) near the epicenter of the 2011 Tohoku earthquake. (b) The variation of this ratio at each station separately during the same period. The black dashed lines can be used as a reference.

4.3. Change of the $Pc3$ amplitude ratio [$ZPc3/HPc3$]

Several studies have reported that earthquakes, in some occasions, are preceded by enhanced Ultra-Low-Frequency (ULF) signals. A remarkable example of the enhancement of the ULF activity before earthquake was observed before the 1989 Loma Prieta earthquake in California; which has been considered as a precursory signal (Fraser-Smith et al., 1990). Since that time, several studies indicate the occurrence of anomalous ULF activities in different frequency ranges in relationship with earthquakes (Hattori et al., 2002; Hayakawa et al., 2007; Yumoto et al., 2009; Takla et al., 2011a,b, 2012). Therefore, the ULF emissions are recently considered as one of the promising tools for monitoring the crustal activities in the seismic active regions.

Natural ULF emissions can be radiated from the hypocenter of earthquakes during their preparation phase. In addition, an enhancement of the ULF waves occurs due to changes in the lithospheric conductivity during the propagation of these waves (Mogi, 1985; Yumoto et al., 2009). In the present study, we present a preliminary result of the ULF emission (in the $Pc3$ range; 10–45 s) that maybe linked with the 2011 Tohoku EQ. We depend on the direct observation of the electromagnetic pulsations to detect any signature of the Tohoku EQ on the $Pc3$ amplitude in the vicinity of the earthquake epicenter. To obtain our goal, we analyze high resolution (1-s) geomagnetic data recorded along an array of five stations extending

from ASB station at the Northern part of Japan up to the LGZ station in Philippines (passing by TNO, ONW and KUJ stations in Japan). Three months data (H-, D- and Z-components from each station) have been fed into a bandpass filter (10–45 s). To clarify the relation between the ULF signal ($Pc3$ range) and the 2011 Tohoku EQ, we calculated the $Pc3$ amplitude ratio ($ZPc3/HPc3$) at these stations as shown in Fig. 6. The $Pc3$ amplitude ratio indicates a possible link between the ULF activity and the 2011 Tohoku EQ. Significant anomalous changes in the $Pc3$ amplitude ratio were observed before the major seismic activity on 11 March 2011. The $Pc3$ amplitude ratio at the ONW station [about 80 km from the epicenter] shows a good correlation with other reference stations during January and the beginning of February 2011. On the other hand, the $Pc3$ amplitude ratio started to show a decreasing trend with no correlation with other stations during the second half of February, as shown in Fig. 6. In addition, the $Pc3$ amplitude ratio is examined during three months after the Tohoku EQ [July–September 2011]. Fig. 7 shows the $Pc3$ amplitude ratio at four geomagnetic stations. It is very clear from Fig. 7 that the $Pc3$ amplitude ratio at ONW shows a clear anti-correlation compared with other reference stations; which reveal significant post seismic underground conductivity changes near the epicenter of the 2011 Tohoku EQ.

A number of mechanisms were proposed to explain the generation of the ULF signals. The piezomagnetic effect (Sasai,

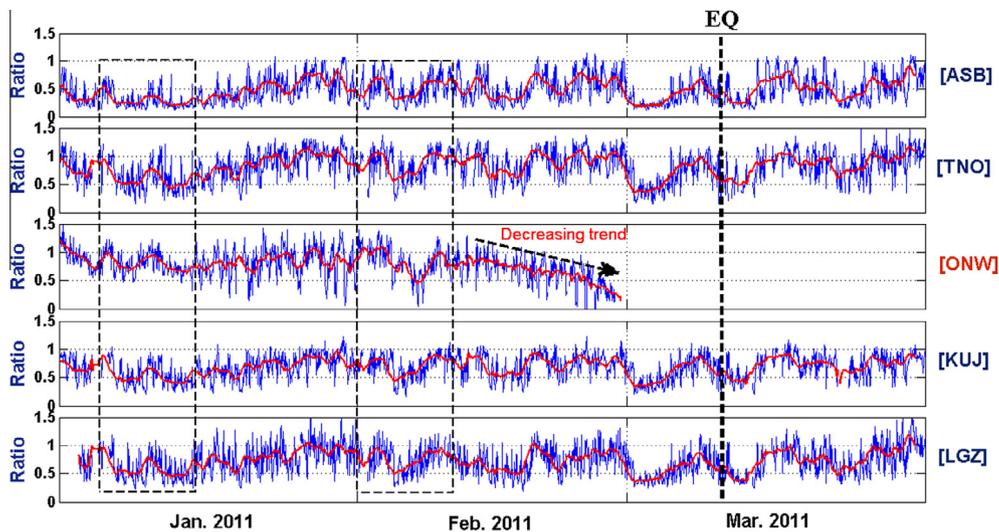


Figure 6 The Pc 3 amplitude ratio (ZPc3/HPc3) observed at some MAGDAS stations during January–March 2011. The red line represents 30 points running average. A clear decreasing trend at ONW station was observed a few weeks before the 2011 Tohoku earthquake with no correlation to other reference stations. The dashed rectangles indicate the correlation among all stations. The magnetometer at ONW station stopped working by the end of February 2011.

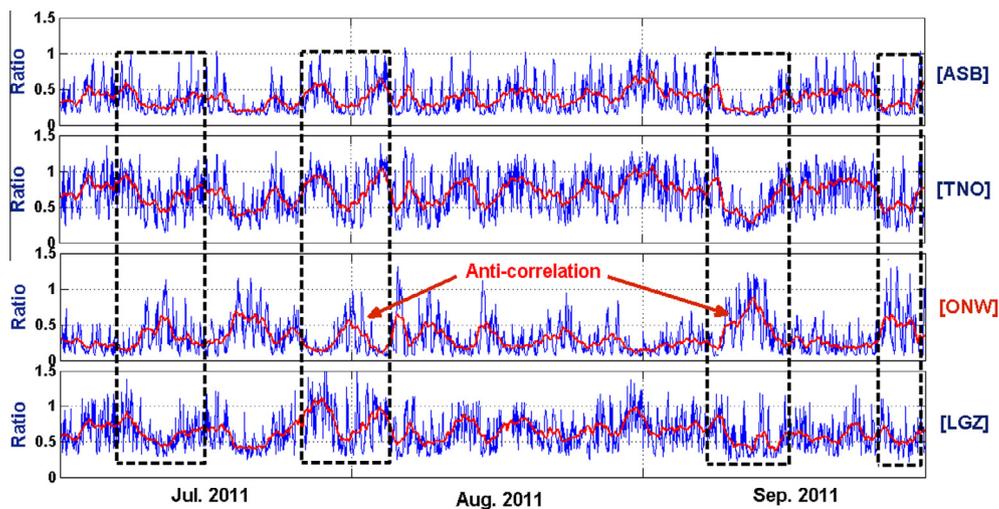


Figure 7 The Pc 3 amplitude ratio (ZPc3/HPc3) observed at some MAGDAS stations during July–September 2011. The red line represents 30 points running average. The dashed rectangles indicate some examples of the anti-correlation at ONW compared with other stations. (At ONW station, there are two magnetometers, and the Pc 3 amplitude ratio from both magnetometers showed anti correlations.)

1991), the electro-kinetic effect (Fitterman, 1979) and the micro-fracturing processes (Molchanov and Hayakawa, 1995) have been considered as sources for generating ULF signals preceding or during earthquakes. The inhomogeneous enhancement of the underground conductivity near the epicenter of the 2011 Tohoku EQ, resulting from stress accumulation and/or underground fluid motion, maybe played an important role for amplifying the ULF emissions of external origin. According to Chi et al. (1996), the amplitude of the electromagnetic emissions recorded on the ground depends on the underground conductivity structure as shown in the following equation:

$$A = B[f(t)]\sigma$$

where, A is the approximate wave amplitude observed on the ground, B is the magnitude of the wave event, $f(t)$ is the local time dependence and σ is the amplification factor which depends on the underground conductivity structure. In this case, the change in the underground conductivity can have an effective impact on the Pc 3 amplitude; which can lead to a precursory anomalous ULF signal especially before large earthquakes. This may explain why the Pc 3 amplitude ratio at the ONW station showed a decreasing pattern before the occurrence of the 2011 Tohoku EQ and also the anti-correlation after the Tohoku EQ. However the exact cause of observed anomalous ULF signals is not fully understood. Further studies are required in order to understand the

physical process or mechanism behind the observed decrease in the Pc 3 amplitude ratio before the 2011 Tohoku EQ and the anti-correlation after the Tohoku EQ.

5. Concluding remarks

The continuous measuring and monitoring of the Earth's magnetic field is the only means to study the different features of this field and especially of its time variations. In the present study, we have highlighted the geomagnetic field variations in Japan in the period between January 2001 and September 2011. Moreover we have shown the existence of some anomalous geomagnetic variations that maybe linked with the 2011 Tohoku earthquake. We can conclude the obtained results as the following:

1. The total geomagnetic field intensity in Japan shows anomalous behavior (increasing pattern) since 2005. Moreover, an increase of about 5 nT in the total geomagnetic field intensity is observed starting from 2009 in the vicinity of the epicenter of 2011 Tohoku EQ (at HAR station) compared with other reference stations.
2. The annual range of the Z-component daily variations tends to decrease near the epicenter [at ONW and HAR stations] before the occurrence of the 2011 Tohoku EQ.
3. The Pc 3 amplitude ratio started to decrease (near the epicenter) a few weeks before the occurrence of the 2011 Tohoku EQ. While, a clear anti-correlation of the Pc 3 amplitude ratio was observed after the Tohoku EQ at ONW station near the epicenter.

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