

Electromagnetic Phenomena Related to the 2011 Tohoku Earthquake and Tsunami: A Short Review

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Abstract

On March 11, 2011, a mega earthquake (magnitude-9.0) occurred off the Pacific coast of Tohoku, north central Japan, followed by a huge tsunami. In this short review, we present information about a variety of up to now published articles reporting different electromagnetic phenomena possibly related to the 2011 Tohoku earthquake or the associated tsunami. The reported anomalies are classified according to the type of electromagnetic phenomenon, while a timeline of occurrence is also provided.

Keywords: Tsunami; Earthquake; Pacific ocean; Geomagnetic field; Ionosphere; Seismo-electromagnetics

Introduction

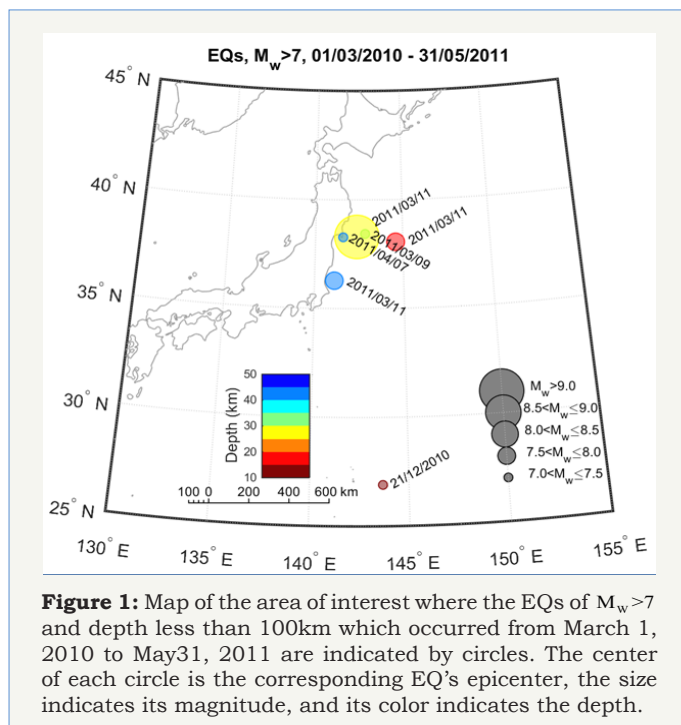


Figure 1: Map of the area of interest where the EQs of $M_w > 7$ and depth less than 100km which occurred from March 1, 2010 to May 31, 2011 are indicated by circles. The center of each circle is the corresponding EQ's epicenter, the size indicates its magnitude, and its color indicates the depth.

On March 11, 2011 a mega earthquake (EQ) of magnitude =9.0 took place at 14:46:18 JST (UT+9h) with its epicenter at the

geographic coordinates (38° 06' N, 142° 52' E) as shown by the larger circle in Figure 1. This was an oceanic EQ of the subduction type (mega thrust EQ) associated with the subduction of the Pacific plate along the Japan Trench. This EQ generated a huge tsunami that struck Japan as well as various locations around the Pacific Ocean, while the tsunami, apart from other damages, caused a cooling system failure at the Fukushima Daiichi nuclear power plant, which resulted in a level-7 nuclear meltdown and release of radioactive materials Mori et al. [1]. As a total 15,893 fatalities and 2,556 missing persons were recorded in different regions of Japan Fujii et al. [2], The National Police Agency [3], while the total material damages (infrastructures, company losses, personal properties, etc.) were of the order of ~\$300-\$450 billion dollars Kazama & Noda [4]. As it is logical, a large number of scientific articles investigating different aspects of these disastrous phenomena were written and are still being published. Different journals published special issues related to them Earth Planets & Space [5,6], Bulletin of the Seismological Society of America [7], Science [8], while review articles with different focuses appear in the literature Okada et al. [9], Tajima et al. [10], Nagao et al. [11], Sato [12].

This short review is focused on presenting different electromagnetic (EM) phenomena possibly related to the Tohoku EQ and the subsequent tsunami which have been reported up to now. However, we have to mention that it is impossible to cite all of the publications. The classification followed in the text is based on



the type of EM phenomenon, since for some observed EM anomalies there has been a dispute on whether they are related to the EQ or the tsunami, or have been attributed to both. Finally, a sorting of

the EM anomalies discussed in this short review according to the timeline of their appearance, with regard to the time of Tohoku EQ occurrence, is provided in the summarizing Table 1.

Table 1:

Occurrence time	Anomaly type	Method of identification	Associated with (EQ, tsunami)	Ref.
$t_0 - \sim 3y, t_0 - 17d$	DC / ULF geomagnetic field components	Ratio of the vertical component difference to the horizontal component difference (dZ/dH); correlation of magnetic field components between stations	EQ	Kopytenko et al. [40]
$(t_0 - 6 \text{ mo}, t_0 - 5 \text{ mo})$	ULF geomagnetic field components	Detrended fluctuation analysis, Higuchi fractal dimension, singular spectrum analysis, correlation analysis	EQ	Potirakis et al. [46]
$t_0 - 2 \text{ mo}$	DC geomagnetic field components	Ratios of diurnal variation range between two stations,	EQ	Xu et al. [43]
$t_0 - 2 \text{ mo}$	DC geomagnetic field components	Ratios of diurnal variation range between two stations, wavelet transform filtering of seasonal events	EQ	Han et al. [44]
$t_0 - 2 \text{ mo}$	DC geomagnetic field components	Temporal-spatial analyses of geomagnetic diurnal variation	EQ	Han et al. [45]
$[t_0 - 14 \text{ d}, t_0 - 12 \text{ d}]$	Monitoring of EM signals of lightning discharges (atmospherics)	Lightning location methods	EQ	Mullayarov et al. [34]
$[t_0 - 10 \text{ d}, t_0 - 5 \text{ d}]$	Monitoring subionospheric VLF/LF propagation	Statistical analysis	EQ	Hayakawa et al. [30-32]
$[t_0 - 10d, t_0 - 1d]$ (max: $[t_0 - 3d, t_0 - 1d]$)	Ionospheric total electron content (GPS-TEC)	Mean, median, wavelet transform, and Kalman filter	EQ	Akhoodzadeh [15]
$[t_0 - 8 \text{ d}, t_0]$	OLR, GPS/TEC, lower Earth orbit ionospheric tomography and critical frequency foF2	Joint analysis of atmospheric and ionospheric parameters	EQ	Ouzounov et al. [37]
$[t_0 - 8 \text{ d}, t_0 - 6 \text{ d}], t_0 - 5 \text{ d}, t_0 - 4 \text{ d}$	ULF geomagnetic field components	Natural time analysis	EQ	Hayakawa et al. [47]
$t_0 - 8 \text{ d}, t_0 - 7 \text{ d}, t_0 - 5 \text{ d},$	ULF geomagnetic field components	Method of critical fluctuations	EQ	Contoyiannis et al. [48]
$t_0 - 6d, t_0 - 3d, t_0$ (max: $t_0 - 3d$)	Ionospheric total electron content (GPS-TEC)	Difference in the diurnal TEC between the estimated GPS-TEC for 20 consecutive days in March, 2011 and the median GPS-TEC for the geomagnetically quiet 7 days in February 2011	EQ	Choi et al. [16]
$[t_0 - 6 \text{ d}, t_0 - 5 \text{ d}]$	ULF magnetic field depression as monitored by ground-based magnetic observatories	Statistical analysis	EQ	Hayakawa et al. [33]
$t_0 - 5 \text{ d}$	NS and EW horizontal components of the ULF/ELF geomagnetic field	Detection of seismo-atmospheric EM radiation and determination of the azimuth of its source	EQ	Ohta et al. [42]
$t_0 - 3d$	Ionospheric total electron content (GPS-TEC)	Comparison of measurements with different models	EQ	Le et al. [17]
$t_0 - 1h$	Ionosonde data, peak plasma frequencies of the F2 and Es layers (foF2, foEs)	Running 30-day median, the International Reference Ionosphere (IRI) model and the Thermosphere Ionosphere Electrodynamics General Circulation Model (TIE-GCM).	EQ	Carter et al. [26]
$t_0 - 40 \text{ min}$	Ionospheric total electron content (GPS-TEC)	Comparison of slant TEC change with models extracted using data of the EQ day (excluding the data of the anomaly period)	EQ	Heki [14]



$t_0 - 40$ min	Ionospheric total electron content (GPS-TEC)	Commenting on Kamogawa & Kakinami [19] and presenting two methods for validating Heki [14] results	EQ	Heki K, and Enomoto Y [20]
$t_0 - 40$ min	Ionospheric total electron content (GPS-TEC)	Commenting on Utada & Shimizu [21]	EQ	Heki and Enomoto [22]
$t_0 - 40$ min	Ionospheric total electron content (GPS-TEC)	Simulation	EQ	Kuo et al. [23]
t_0 (coseismic)	DC geomagnetic total intensity	Time series values after correcting the effect of external disturbances and induced fields	EQ	Utada et al. [39]
$[t_0, t_0 + 1$ h]	DC geomagnetic field total intensity	Time series values after correcting the effect of external disturbances and induced fields	tsunami	Utada et al. [39]
$[t_0, t_0 + 1$ h]	DC geomagnetic field components	Spectrum analysis, Rayleigh wave model of seismo-ionospheric disturbances	EQ and tsunami	Hao et al. [41]
$t_0 + 7$ min	Ionospheric total electron content (GPS-TEC)	Band - pass filtered GPS - TEC	EQ and tsunami	Liu et al. [13]
$t_0 + 9$ min	Continuous Doppler sounding system	Doppler shift spectrograms, comparison with models	EQ	Chum et al. [29]
$[t_0 + 10$ min, $t_0 + 80$ min]	Ocean-bottom electromagnetometer	Analysis of magnetic field components and offshore sea-level data	tsunami	Ichihara et al. [51]
$t_0 + 15$ min	Ionospheric total electron content (GPS-TEC)	Comparison of slant TEC change with models extracted using data on the similar GPS satellite orbit on a day other than the EQ day.	tsunami	Kakinami et al. [18]
$t_0 + 15$ min	Ionospheric total electron content (GPS-TEC)	Commenting on Heki[14] & Kakinami et al. [18] results	tsunami	Kamogawa & Kakinami [19]
$t_0 + 15$ min	Ionospheric total electron content (GPS-TEC)	Simulation	tsunami	Shinagawa et al. [25]
$t_0 + 15$ min	Ionospheric total electron content (GPS-TEC)	Commenting on Heki, K., & Enomoto, Y. [20]	tsunami	Utada & Shimizu [21]
$t_0 + 15$ min	Ionosonde data, peak plasma frequency of the F2 layer (foF2)	Height derivative of the plasma frequency as a function of time and height and other methods	EQ	Berngardt et al. [27]
$[t_0 + 15$ min, $t_0 + 30$ min]	Ionosonde data, peak plasma frequency of the F1, F2, and Es layers (foF1, foF2, foEs)	Simulation, comparison with seismograms	EQ	Maruyama & Shinagawa [28]
$t_0 + 1$ h	Ionospheric total electron content (GPS-TEC)	Analytical description and measurement data	tsunami	Occhipinti et al. [24]
$[t_0 + 60$ min, $t_0 + 80$ min]	Ocean-bottom electromagnetometer	Several analysis methods	tsunami	Zhang et al. [52]
$t_0 + \sim 1$ h	Vertical component (Z) of the DC geomagnetic field	Comparison of magnetic field and sea-level changes, simulation	tsunami	Tatehata et al. [49]
$t_0 + \sim 1$ h	Vertical component (Z) of the DC geomagnetic field	Travel time diagram of the magnetic disturbances, correlation analysis	tsunami	Klausner et al. [50]
$[t_0 + 1$ h, $t_0 + 1.5$ h]	Monitoring subionospheric VLF/LF propagation	Statistical analysis	tsunami	Rozhnoi et al. [35]
$t_0 + 1.5$ h	Monitoring subionospheric VLF/LF propagation	Statistical analysis, comparison to the in-situ sea-level GPS measurements	tsunami	Rozhnoi et al. [36]
$t_0 + 2.33$ h	Doppler shift measurements, GPS/TEC, magnetic field	multi-instrument-based study	EQ and tsunami	Hao et al. [38]

Ionosphere anomalies

Different kinds of ionosphere anomalies have been reported to be related, or have been investigated for possible relation, with the 2011 Tohoku EQ and/or tsunami. These include ionosphere total electron content (TEC) anomalies, infrasonic waves, disturbances of peak plasma frequencies of different layers, ultra-low frequency (ULF) magnetic field depression, and very-low/low (VLF/LF) lower ionospheric perturbation. Specific articles concerning each one of these categories are briefly discussed in the following.

GPS-TEC anomalies

Liu et al. [13] reported TEC anomalies derived from nationwide global positioning system (GPS) receiving networks in Japan and Taiwan, attributing them to the traveling of Earth surface and tsunami motions up to the ionosphere. The first anomalies observed by Liu et al. [13] appeared as a disk-shaped TEC increase about 7 min after the EQ occurrence. Heki [14] reported that the Japanese network of GPS detected a precursory positive TEC anomaly around the focal region, which started ~ 40 minutes before the Tohoku EQ and reached nearly ten percent of the background TEC, while it lasted until atmospheric waves arrived at the ionosphere. The method used was a comparison of slant TEC change with TEC models Heki [14]. A precursor to the Tohoku EQ was also reported by Akhoondzadeh [15] who using four methods, mean, median, wavelet transform, and Kalman filter, detected a considerable number of anomalous occurrences during 1 to 10 days prior to the EQ. The highest deviations from the normal state that were regarded as anomaly appeared within the time interval 1-3 days before the EQ. Based on measurements of the GPS network of on the Korean Peninsula, Choi et al. [16] detected ionosphere TEC anomalies during the daytime. Specifically, they reported that an increase in TEC appeared on March 5, 8 and 11, while the March 8 ones were remarkable. Le et al. [17] also reported a significant enhancement in TEC on March 8, 2011, probably related to the Tohoku EQ. Yet, they suggest that the detected anomalies may also be contributed partly by the geomagnetic disturbance (Kp=4) which occurred on March 7.

Moreover, Kakinami et al. [18] were focusing on the so-called "tsunamigenic ionospheric hole", which is a sudden depletion of ionospheric TEC in the hundred kilometer scale and lasts for a few tens of minutes over the tsunami source area. They concluded that this kind of phenomenon appears only in cases of large EQs followed by tsunamis and not in the case of inland large EQs. Then, Kamogawa & Kakinami [19] commented on Heki [14] findings compared with those of Kakinami et al. [18] suggesting that the anomaly reported by Heki [14] is a false one resulted by inappropriate model reference. The difference between Heki [14] and Kakinami et al. [18] is attributed to the reference curves of the TEC to extract the ionosphere variations. The former is given by the least-squares fitting curve of the EQ day data excluding an expected precursor period, while the latter is given by the data of the similar orbit of GPS satellite on another day. Later, Heki & Enomoto [20] published a rebuttal to this by employing two new methods for

the validation of Heki [14] findings, while Utada & Shimizu [21] further investigated this issue by concluding that the observation of anomalous declination changes before the Tohoku EQ does not confirm the reality of the precursory TEC enhancement. Finally, Heki & Enomoto [22] questioned part of the conclusions of Utada & Shimizu [21] regarding the validity of the Heki [14] precursor, concluding though that the relation between geomagnetic variations and TEC disturbances should be further investigated in the future. Kuo et al. [23] applied their improved lithosphere-atmosphere-ionosphere (LAI) coupling model to compute the TEC variations and compare the simulation results with the Heki [14] reported TEC observations related to Tohoku EQ and determined the necessary conditions in order for the reported anomaly to be reproduced by the specific model.

Referring to data from Tohoku EQ, but also other tsunamigenic EQs, Occhipinti et al. [24] deal with the discrimination of TEC anomalies related to the acoustic-gravity waves generated at the epicenter by the direct vertical displacement of the source rupture and those related to the gravity wave coupled with the tsunami. They used an analytical (theoretical) description of the involved phenomena for this purpose. Also based on the TEC anomalies observed after the Tohoku EQ, Shinagawa et al. [25] proceeded with a simulation study based on a two-dimensional nonlinear non hydrostatic compressible atmosphere-ionosphere model. They concluded that an impulsive pressure pulse produced by a sudden uplift of the sea surface leads to local atmospheric expansion in the thermosphere and that the expansion of the thermosphere combined with the effect of inclined magnetic field lines in the ionosphere causes the sudden TEC depletion above the epicenter region.

Peak plasma frequency anomalies and infrasound waves

Before the Tohoku EQ, an anomaly in the peak plasma frequencies of the F2 layer (foF2) and the Es layer (foEs) was reported by Carter et al. [26]. By using ionosonde data and three separate baselines for foF2, the running 30-day median, the International Reference Ionosphere (IRI) model and the Thermosphere Ionosphere Electrodynamics General Circulation Model (TIE-GCM), they found that a simultaneous increase in foF2 and foEs relative to the 30-day median happened within 1 h before the EQ. However, in lack of statistical evidence, they concluded that one cannot confidently use this type of ionospheric perturbation to predict an impending EQ. On the other hand, Berggardt et al. [27] studied the dynamics of vertical ionospheric irregularities caused by Tohoku EQ based on the data obtained from Irkutsk CHIRP ionosonde, at 3400 km distance from the EQ epicenter. They concluded that the identified irregularities, 06:00 to 06:20 UT, are qualitatively explained by traveling of the acoustic shock wave cone.

Strong deformation of ionogram echo traces, forming multiple cusp signatures (MCSs), were observed at three stations 790-1880 km from the epicenter Maruyama & Shinagawa [28]. It was concluded that the travel time diagram of the seismic records along the line connecting the epicenter and ionosondes showed that the



rest MCS ionogram detected at each station was caused by P waves, while the others were caused by Rayleigh waves. A train of large amplitude infrasound wave packets was observed by multipoint continuous Doppler sounding system in the ionosphere over the Czech Republic on March 11, 2011. Chum et al. [29] showed that these infrasound wave packets originated from vertical motion of the ground surface that was caused by arrival of seismic waves generated by the strong Tohoku EQ.

Lower ionosphere disturbances

By using the network observations of sub-ionospheric VLF/LF signals in Japan and Russia, Hayakawa et al. [30,31] found a significant ionospheric perturbation prior to the Tohoku EQ. Specifically, a remarkable decrease was detected in the nighttime amplitude and increase in the dispersion on March 5 and 6, on the paths from NLK (Seattle, USA) to Chofu, Kochi and Kasugai, while anomalies were also found in March 1-6 period and minima in the nighttime amplitude on March 3 and 4 on the path JJI (Miyazaki, Kyushu) - Kamchatka, Russia. Moreover, different aspects of the observed phenomenon, the possible relation with other phenomena, the existence of similar perturbations and a possible generation mechanism were extensively investigated in Hayakawa et al. [32].

Additionally, another phenomenon reflecting sub-ionospheric perturbations, the depression of the magnetospheric ULF emissions observed on ground-based stations was reported by Hayakawa et al. [33] as a possible precursor to the Tohoku EQ. Clear depression of the ULF magnetic field happened on March 5 and 6, during a period that VLF/LF propagation anomaly was also found. The monitoring of lower ionosphere disturbances by means of detection of natural radio emissions, i.e. EM signals of lightning discharges (atmospherics) also revealed possible precursors of the Tohoku EQ and a M7.3 EQ which happened very close to it two days before, as well disturbances after Tohoku EQ Mullayarov et al. [34].

Finally, tsunami-induced subionospheric anomalies (both in the amplitude and phase) have also been reported after the Tohoku EQ and tsunami by means of VLF/LF propagation monitoring Rozhnoi et al. [35,36] The observed effects in the ionosphere were compared to the in-situ sea-level GPS measurements near Japan Rozhnoi et al. [36], while a qualitative interpretation of the observed effects was suggested in terms of the interaction of internal gravity waves with lower ionosphere Rozhnoi et al. [35].

Multi-instrument revealed anomalies

Ouzounov et al. [37] retrospectively analyzed the temporal and spatial variations of four different physical parameters characterizing the state of the atmosphere and ionosphere several days before the Tohoku EQ. They used outgoing long wave radiation (OLR), GPS/TEC, lower Earth orbit ionospheric tomography and critical frequency foF2 data and found different kinds of anomalies in the time period March 3 to 11, 2011. Moreover, in a multi-instrument-based study, Hao et al. [38] observed in Beijing, by a local infrasound detector, surface-oscillation-excited ionospheric

anomalies related to the Tohoku EQ. The ionosphere disturbances were detected by HF Doppler shift measurements as well as by fluctuations of GPS/TEC. They also suggested that interactions between the electron density variation and ionospheric current were manifested by geomagnetic field is turbines measured by ground-based magnetometers. Hao et al. [38] reported that infrasonic waves excited around the epicenter or tsunami area propagated horizontally in the atmosphere and were received by the infrasound detector in Beijing 2h and 20 min later at a distance of about 2400-2500 km from their source region.

Geomagnetic field anomalies

The possible relation of magnetic anomalies recorded by ground-based or sea-bottom magnetic observatories with the 2011 Tohoku EQ and/or tsunami, has been extensively investigated. Specific articles concerning each one of these categories are briefly discussed in the following.

Ground-based magnetic field anomalies

Simultaneous measurements of the geomagnetic field in association with the Tohoku EQ and tsunami by magnetometers at 14 stations operating in Japan were reported by Utada [39]. They found a coseismic change of the main geomagnetic field (DC geomagnetic field) observed at several stations located relatively close to the epicenter. Moreover, they reported distinct and rapid changes during the hours following the main shock attributed either to the motional induction of the tsunami or to ionospheric disturbance.

Kopytenko et al. [40] reported that disturbances both in the main magnetic field of the Earth and in ULF geomagnetic field variations ($f < 10\text{Hz}$) were observed before the Tohoku EQ. Secular variations of the main geomagnetic field were investigated using three-component 1-h data from three magnetic observatories over the 11-year period of January 1, 2000, to January 31, 2011. They used data from the Esashi and Mizusawa magnetic stations (situated northwest of the EQ epicenter, at distances $\sim 170\text{km}$ to 200km), as well as from the Kakioka observatory (situated southwest of the EQ epicenter, at a distance of $\sim 300\text{km}$). During this period, they found four local anomalies in the secular variations, the last of which (the biggest) began around 3 years prior to the EQ. Concerning the ULF magnetic field variations, they analyzed three-component 1-s data at two magnetic stations (Kakioka and Uchiura).

The Uchiura station is situated south to Kakioka, at a distance of $\sim 420\text{km}$ from the EQ epicenter. They found that a decrease in the correlation coefficients of the corresponding magnetic components at these two stations happened from February 22, 2011. Differences in the Z components showed an increase, and became positive after this date. They concluded that this might suggest that the ULF lithospheric source appeared north of the Kakioka station. Anomalous magnetic variations, teleseismic magnetic effects (TMDs), due to the Tohoku EQ were reported by Hao et al. [41] which were still notable at stations 2000-4000km away from the epicenter. They suggested that these TMDs were not generated by

direct effects of processes in the focal area crust or tsunami waves; instead, their properties consisted with the Rayleigh wave model of seismo-ionosphere disturbances. They suggested that these were the magnetic manifestation of seismo traveling ionospheric disturbances (STIDs) generated by the interaction between the ionosphere and atmosphere through acoustic waves launched by traveling Rayleigh waves.

The ULF/ELF short-term EM precursor was reported by Ohta et al. [42] that was identified 5 days before the Tohoku EQ, using data from search coil magnetometers of the Chubu University network. A confirmation on its seismic origin was provided by the observational fact that the azimuths of the radiation source from all observation sites coincided approximately with the region of the forthcoming EQ. Moreover, the unusual behavior of geomagnetic diurnal variations 2 months prior to the Tohoku EQ were reported by Xu et al. [43] by calculating ratios of diurnal variation range between the target station Esashi (ESA), ~ 135km from the epicenter, and the remote reference station Kakioka (KAK), ~ 302km from the epicenter. The original records of geomagnetic fields of the ESA station also exhibited continuous anomalous behavior for about 10 days in the vertical component ~2 months prior to the EQ.

The study of the geomagnetic diurnal variations anomaly related to the Tohoku EQ was further investigated by Han et al. [44] by analyzing geomagnetic data of 16 years' long term observation. They found that, after removing seasonal variations revealed by wavelet transform analysis, the 15-day mean values of the ratios in the vertical component shows a clear anomaly exceeding the statistical threshold about 2 months before the mega event. The investigation of geomagnetic diurnal variation anomaly prior to the Tohoku EQ was further extended to temporal-spatial analysis of long-term observations at 17 stations in Japan by Han et al. [45]. Their analysis ended-up to the same results about the time of occurrence of the precursory behavior. Moreover, the locations of anomalies in spatial distribution showed a good correlation with the epicenter of the Tohoku EQ, while the obtained spatiotemporal results were found to be consistent with those obtained from other independent observations such as groundwater level and GPS displacements.

Furthermore, a fractal analysis of the ULF magnetic field variations prior to the Tohoku EQ with the use of detrended fluctuation analysis (DFA) and Higuchi fractal dimension algorithm was presented by Potirakis et al. [46], aiming at discriminating between possible EQ precursors from space-sourced disturbances. Fractal analysis results revealed a change in fractal characteristics, namely a gradual reduction in DFA α -exponent values and corresponding gradual increase in Higuchi fractal dimension values, 5-6 months before the Tohoku EQ. The observed changes were recovered after the occurrence of the EQ. The extensive filtering and correlation analyses performed suggest, according to the authors, that the observed disturbance was locally driven sourced at the EQ preparation processes and not related to space-sourced disturbances.

By applying natural time (NT) analysis on daily values of ULF magnetic field characteristics calculated on the basis of the magnetic field components' power during low noise nighttime intervals, Hayakawa et al. [47] found that criticality features appear in the geomagnetic field variations 8-6, 5 and 4 days prior to the Tohoku EQ occurrence. They suggested that these findings reflect the critical condition reached by the lithosphere, either as embedded into direct emissions (8-6 days before the EQ) or as embedded in the geomagnetic signature (horizontal field depression) of ionosphere disturbance (5 and 4 days before the EQ). The critical behavior of ULF magnetic field variations was further verified by Contoyiannis et al. [48] after applying a completely different analysis method, the method of critical fluctuations (MCF), on the raw magnetic field recordings. Specifically, they found clear signatures of intermittent criticality in the recordings of 4 March 2011, while indications of critical behavior were also found in 3 and 6 March recordings, although not of the "stability" of those of 4 March. Moreover, it was found that only the ULF data of the geomagnetic observatory nearest to the EQ epicenter presented criticality. This finding further corroborates the view that the presented signal is indeed a precursor to the specific EQ.

Beginning from the fact that the vertical component of the magnetic field at Chichijima Island, 1200km south of the epicenter of Tohoku EQ presented a periodic signal at approximately 20min before the tsunami arrived, Tatehata et al. [49] compared the sea-level changes and magnetic field variations after the EQ. Furthermore, using a simulation, they investigated the mechanism producing the observed magnetic field signal and tried to confirm that the oceanic dynamo effect caused the magnetic field variations. They found that the vertical component of the geomagnetic field and the tide gauge records at Chichijima Island exhibited very similar patterns. Moreover, they concluded that the straight-line electric current induced a secondary magnetic field that curled at the front of the first tsunami wave.

Klausner et al. [50] examined the effects of Tohoku EQ tsunami to the vertical component (Z) of the geomagnetic field observed by 9 ground-based observatories distributed along the tsunami passage, covering up to 3000km epicentral distance. They identified the amplified magnetic disturbances appearing during the tsunami arrival in the vicinity of the specific observatories and examined the cross correlations among different observatories and the amplified disturbances. These were found to be highly correlated, concluding that this result suggests that the observed magnetic field disturbances were tsunamigenic.

Sea-bottom magnetic field anomalies

A tsunami induces secondary EM fields of significant intensity as a result of Faraday's law, and these EM fields can be recorded by instruments on the sea floor. Tsunami-induced magnetic signals related to the tsunami triggered by the Tohoku EQ from an ocean-bottom electro magnetometer emplaced 50km east of the Japan Trench were reported by Ichihara et al. [51]. They suggested that the impulsive variation of the vertical magnetic field component



directly indicates the tsunami wave height and arrival time at the station, while the impulsive variation of the horizontal magnetic components indicates the tsunami-propagation direction. They determined the tsunami source ~100km northeast from the main rupture area and using joint analyses of the observed magnetic variations and offshore sea-level data verified this source location and that the tsunami origin time was about 1min after the EQ origin time. In addition, they suggested that the magnetic field variation and the sea level change indicate that the source area was elongated in the trench direction and had a narrow width.

Zhang et al. [52] reported the observation of Tohoku tsunami-induced EM signals, recorded by a small array of ocean bottom electro-magnetometers consisting of four stations in the northwestern Pacific Ocean. They used several data analysis methods to estimate tsunami parameters.

The wave height was estimated from the observed magnetic and electric fields, while the propagation direction the tsunami was estimated by applying analysis methods for an array and a single station. A related three-dimensional simulation study was published by Zhang et al. [53] concerning the Tohoku tsunami-induced EM signals detected by seafloor magneto telluric stations. Their simulation results were in agreement with both ground-based and sea-bottom magnetic observations, while they found that the field of the primary toroidal magnetic mode can be effective for seafloor observations but only when the seafloor is highly conductive.

Conclusion

From this short review it is obvious that a great variety of EM phenomena appeared before and after the Tohoku EQ and the associated tsunami. Some of them have been attributed to the EQ preparation processes and have been proposed as possible EQ precursors, others have been associated to the ground/sea level motions due to seismic motion and others have been credited to the tsunami that followed this mega EQ. All of the up to now published articles, elucidate different aspects of these phenomena and contribute to better understanding of their sources, their interactions, as well as efficient ways to observe and discriminate them. Future development of the multidisciplinary field of EM phenomena related to EQs and tsunamis may increase our efficiency in predicting these natural hazards in order to avoid or minimize disasters.

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