On the anomalous changes of seismicity and geomagnetic field prior to the 2011 $M_w$ 9.0 Tohoku earthquake

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Xu et al. [J. Asian Earth Sci. 77, 59-65 (2013)] It has just been reported that approximately 2 months prior to the $M_w$ 9.0 Tohoku earthquake that occurred in Japan on 11 March 2011 anomalous variations of the geomagnetic field have been observed in the vertical component at a measuring station about 135 km from the epicenter for about 10 days (4 to 14 January 2011). Here, we show that this observation is in striking agreement with independent recent results obtained from natural time analysis of seismicity in Japan. In particular, this analysis has revealed that an unprecedented minimum of the order parameter fluctuations of seismicity was observed around 5 January 2011, thus pointing to the initiation at that date of a strong precursory Seismic Electric Signals activity accompanied by the anomalous geomagnetic field variations. Starting from this date, natural time analysis of the subsequent seismicity indicates that a strong mainshock was expected in a few days to one week after 08:40 LT on 10 March 2011.

I. INTRODUCTION

Several papers have reported various electromagnetic signals being detected before large earthquakes in Greece [1-4], Japan [5, 6], California [e.g., 7, 8, see also Bleier et al. 10 and references therein] and China [11, 12]. Xu et al. [13] just reported unusual behavior of geomagnetic diurnal variations prior to the Tohoku earthquake of magnitude $M_w$ 9.0 that occurred in Japan on 11 March 2011. They computed ratios of diurnal variations range between the target station Esashi (ESA) located at about 135 km from the epicenter and the remote reference station Kakioka (KAK) about 302 km distant to the epicenter. Their results showed a clear anomaly exceeding the statistical threshold in the vertical component about 2 months before the earthquake occurrence. The original records of geomagnetic fields of the ESA station also exhibited anomalous behavior for about 10 days (4 to 14 January 2011) in the vertical component approximately 2 months before the $M_w$ 9.0 earthquake. It is the objective of this short paper to show that these findings of Xu et al. [13] are in full accord with recent results published independently [14, 15] on the basis of the analysis of seismicity of Japan in a new time domain - termed natural time [16], which reveals some dynamic features hidden in the time series of complex systems [17, 18].

Natural time analysis [16, 19, 21] has found applications in diverse fields and the relevant results have been compiled by Varotsos et al. [18]. In the case of seismicity, in a time series comprising $N$ earthquakes, the natural time $\chi_k = k/N$ serves as an index for the occurrence of the $k$-th earthquake. In natural time analysis we study this index in conjunction with the energy $Q_k$ released during the $k$-th earthquake of magnitude $M_k$, i.e., the pair $(\chi_k, Q_k)$. Alternatively, one employs the pair $(\chi_k, p_k)$, where

$$p_k = \frac{Q_k}{\sum_{n=1}^{N} Q_n} \quad (1)$$

denotes the normalized energy released during the $k$-th earthquake. It has been found [18–22] that the variance of $\chi$ weighted for $p_k$, designated by $\kappa_1$ given by

$$\kappa_1 = \sum_{k=1}^{N} p_k (\chi_k)^2 - \left( \sum_{k=1}^{N} p_k \chi_k \right)^2 \quad (2)$$

plays a prominent role in identifying when a complex system approaches the critical point.

Since the observed earthquake scaling laws [e.g. see 23] are widely accepted to indicate the existence of phenomena closely associated with the proximity of the system to a critical point [e.g., 24, 27], Varotsos et al. [22] took the view that earthquakes are (non-equilibrium) critical phenomena and argued that the quantity $\kappa_1$ given by Eq. (2) can be considered as an order parameter for seismicity. It has been found [18, 19, 28, 29] that a mainshock occurs in a few days to one week after the $\kappa_1$ value is recognized to have approached 0.07 in the natural time analysis of the seismicity subsequent to the initiation of a Seismic Electric Signals (SES) activity. This is made on the premise that the initiation of an SES activity marks the time when the system enters the critical regime based on the following grounds: The SES, which are low frequency transient changes of the electric field of the Earth that precede earthquakes and their physical properties enable the determination of the epicenter and the magnitude of an impending earthquake [1, 2, 30], are probably generated by means of the so called pressure stimulated polarization currents (PSPC) model proposed by Varotsos and Alexopoulos [31] [see also 32]. This model, which motivated the SES research, makes use of the widely accepted concept that the stress gradually increases in the future focal region of an EQ. When this stress reaches a critical value, a cooperative orientation of the electric dipoles (which are anyhow present in the focal area due to lattice imperfections in the ionic constituents of the rocks, e.g., see [33, 34]) is attained. This leads to the emission of a transient electric signal that constitutes an SES (the...
cooperativity is a hallmark of criticality). The validity of this SES generation mechanism is strengthened by the finding that the up to date experimental data of SES activities have been shown to exhibit infinitely ranged temporal correlations [20, 21, 35], which conforms with the aspect of critical dynamics. As pointed out by Uyeda et al. [6], the PSPC model is unique among other models in that SES would be generated spontaneously during the gradual increase of stress without requiring any sudden change of stress such as microfracturing [37] or faulting [38].

The up to date observations of the magnetic field variations accompanying the SES activities have shown that they are clearly detectable at distances of the order of ~100 km for strong EQs, i.e., of magnitude 6.5 or larger [e.g., see 39]. In addition, as demonstrated by detailed computations [40], these magnetic field changes mainly appear in the Z component as observed by Xu et al. [13]. This will be further discussed below.

II. NATURAL TIME ANALYSIS OF SEISMICITY IN JAPAN. RECENT RESULTS AND THEIR RELATION WITH THE FINDINGS OF XU ET AL. [11]

By analyzing the Japanese seismic catalog in natural time, and employing a sliding natural time window comprising the number of events that would occur in a few months, the following results have been recently published:

Varotsos et al. [14] found that the fluctuations of the order parameter \( \kappa_1 \) of seismicity exhibit a clearly detectable minimum approximately at the time of the initiation of the pronounced SES activity observed by Uyeda et al. [5, 6] almost two months before the onset of the volcanic-seismic swarm activity in 2000 in the Izu Island region, Japan. This reflects that presumably the same physical cause led to both effects observed, i.e., the emission of the SES activity and the change of the correlation properties between the earthquakes. This might be the case when the stress reaches a critical value, if we recall the PSPC model (mentioned above in Section I) for the SES generation. In addition, Varotsos et al. [14] reported that the aforementioned two phenomena were found to be also linked in space.

Note that for the vast majority of major earthquakes in Japan the almost simultaneous appearance of these minima with the initiation of SES activities cannot be checked due to the lack of geoelectrical data. In view of this lack of data, Sarlis et al. [15] proceeded to the analysis of the Japanese seismic catalog in natural time from 1 January 1984 to 11 March 2011, the day of the \( M_{w} 9.0 \) Tohoku earthquake. They found that the fluctuations of the order parameter of seismicity exhibited distinct minima a few months before all the shallow earthquakes of magnitude 7.6 or larger that occurred during this 27 year period in Japanese area. Among the minima, the minimum before the \( M_{w} 9.0 \) Tohoku earthquake observed on ~5 January 2011 was the deepest. Sarlis et al. [15] ended their conclusion by pointing out that "the approximate coincidence of the lead time of the SES activity and the change of the correlation of seismicity with that of the SES activities may help in understanding the physics of both phenomena". This, reflects that for the case of the aforementioned deepest minimum of seismicity before the Tohoku earthquake observed on ~5 January 2011, a strong SES activity should have been initiated on the same date. Consequently, as mentioned in Section I anomalous magnetic field changes accompanying the electric field variations of this SES activity should also initiate on this date, i.e., 5 January 2011. It is this expectation which is strikingly verified by Xu et al. [13] who reported that anomalous magnetic field variations at Esashi station initiated on ~4 January and lasted almost 10 days.

III. DETERMINATION OF THE OCCURRENCE TIME OF TOHOKU \( M_{w} 9.0 \) EARTHQUAKE.

The SES activities are considered as mentioned above to occur when the focal zone enters the critical stage. The date of the minimum (~5 January) of the order parameter fluctuations of seismicity determined by Sarlis et al. [12] –which almost coincides with the starting date of the magnetic field variations identified by [13] could be considered as the time of the initiation of the SES activity. Assuming that this is the case, we started the computation of the \( \kappa_1 \) values of seismicity from this time in each of all the subareas [18, 28] in a region \( 3^\circ \times 3^\circ \) surrounding the epicenter of Tohoku earthquake (EQ), i.e., in the area \( N^{39.5}E^{144} \) by using the Japan Meteorological Agency (JMA) earthquake catalogue. (Hereafter, the corresponding magnitudes are labelled \( M_{JMA} \).) Seismic moment \( M_0 \) and thus the seismic energy was obtained from the moment magnitude \( M_w \) by applying the following approximate formulae obtained by Tanaka et al. [41]

\[
M_0 = 10^{1.5M_w}
\]

From these \( \kappa_1 \) values, Fig. 1 has been constructed showing the probability distribution \( P(\kappa_1) \) of \( \kappa_1 \) on several dates just before the main shock. The calculation was made for various \( M_{JMA} \) thresholds. These thresholds have been selected, as it should for the study of seismicity changes [e.g., 43], to exceed the value \( M_{JMA} = 3.4 \) above which Sarlis et al. [15] found that the JMA earthquake catalogue is complete by analyzing the data since 1 January 1984 until the \( M_{w} 9.0 \) Tohoku earthquake occurrence within the area \( N^{39.5}E^{144} \) practically covering the whole Japanese region. Examples are given in Figs. 1(a), (b) and (c), for \( M_{JMA} > 3.4 \), 3.9 and 4.8, where 113, 73 and 30 EQs have been used into the calculation, respectively. The cyan crosses depict \( P(\kappa_1) \) at the end of February, i.e., at 00:38 LT on 27 February, while the magenta "x" shows \( P(\kappa_1) \) almost two hours after the \( M_{w} 7.3 \) foreshock that occurred at 11:45 LT on 9 March 2011. We
observe that $P(\kappa_1)$ was displaced in the latter to lower $\kappa_1$ values close to zero. At later times, i.e., almost 9 (blue), 16 (green) and 21 (red) hours after the foreshock, the height of $P(\kappa_1)$ close to zero became smaller and $P(\kappa_1)$ finally exhibited a local maximum at 0.07 around 08:40 LT on 10 March 2011 (see the black vertical arrows in the insets). The main shock could have happened at any moment after this, as mentioned in Section 4. It is remarkable that the condition $\kappa_1 = 0.07$ was not observed, in a wide range of magnitude thresholds, before the aforementioned $M7.3$ foreshock indicating the system has not reached yet the critical point at that stage.

IV. CONCLUSIONS

By analyzing the seismicity of Japan in natural time, Sarlis et al. [15] have found that the fluctuation of the order parameter $\kappa_1$ exhibited unprecedented minimum around 5 January 2011, i.e., almost 2 months before 11 March $M_{w}9$ Tohoku EQ. This date is likely to coincide with the initiation of a SES activity when considering the conclusions drawn [14] from earlier cases in Japan where both seismic data and geoelectrical data were available. Actually, Xu et al. [13] found that the anomalous magnetic field variations started on 4 January 2011, i.e., approximately on the same date. Here, it is also found that the $\kappa_1$ values of seismicity computed after this date converged to $\kappa_1 = 0.07$ at 08:40 LT on 10 March 2011, i.e., the day before the Tohoku EQ occurrence, thus signalling the impending risk. Quite interestingly, these $\kappa_1$ values did not converge to 0.07 before the 9 March $M7.3$ EQ, indicating that the critical point was not reached at the stage of this foreshock. This fact may provide the means of identifying whether an EQ is a foreshock or a main shock when natural time analysis is employed.

In a separate publication (Sarlis, Skordas and Varotsos to be published), we draw attention to the following point motivated by the aspects of the PSPC model: Changes in the correlation properties of other associated physical quantities [4, 44] like crustal deformation orientation [44] (by analyzing GPS measurements) have been observed approximately on the same date(s).

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FIG. 1: (color) The probability $P(\kappa_1)$ of finding a value in the range $\kappa_1 \pm 0.0025$ as a function of $\kappa_1$ for the seismicity after 5 January 2011. The values of $\kappa_1$ have been found by studying all the possible subareas within the area $\lambda_{36.5} \lambda_{144}$ for three $M_{JMA}$ thresholds. The insets are enlarged excerpts around $\kappa_1 = 0.07$. The dates and times are for the last EQ considered in each calculation.