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Direct interconnection of seismicity with variations of the Earth's electric and magnetic field before major earthquakes

P. A. Varotsos[(a)], N. V. Sarlis and E. S. Skordas

Section of Condensed Matter Physics and Solid Earth Physics Institute, Physics Department, National and Kapodistrian University of Athens - Panepistimiopolis, Zografos 157 84, Athens, Greece, EU

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Abstract – Upon employing the new concept of time, termed natural time, the analysis of seismicity reveals that, before major earthquakes, the variations of the Earth's electric and/or magnetic field are accompanied by increase of the fluctuations of the entropy change of seismicity under time reversal as well as by decrease of the fluctuations of the seismicity order parameter. Hence, natural time analysis reveals that before major earthquakes independent datasets of different geophysical observables (seismicity, Earth's magnetic and/or electric field) exhibit changes, which are observed simultaneously.

To the memory of the Academician Seiya Uyeda.

In a previous publication [1] it was shown that sudden cardiac death (SCD), which is a frequent cause of death and may occur even if the electrocardiogram (ECG) seems to be similar to that of a healthy individual, can be identified in advance as well as provide an estimation of the time of an impending cardiac arrest if the ECG analysis is made in an entirely different time domain from the conventional time, *i.e.*, the natural time domain (which extracts the maximum information possible from a time series, see ref. [2]). This has been achieved by means of the entropy change ΔS of the entropy S defined in natural time upon reversing the direction of the time arrow (see below), which plays an important role when a complex system approaches a dynamic phase transition (cf. we note that natural time has been also employed by Rundle, Turcotte and coworkers as a basis of a new methodology termed earthquake nowcasting, to estimate the current seismic risk [3–5]). On the basis of the same quantity ΔS, here we show that we may identify the approach of major earthquakes (EQs) upon analyzing the seismicity in natural time being accompanied by anomalous variations of the Earth's electric and/or magnetic field (see ref. [6]). In particular, here we focus on the magnitude (M)9.0 Tohoku EQ that occurred in Japan on 11 March 2011 —which is the largest EQ ever recorded in Japan— and the volcanic-seismic swarm activity in 2000 in the Izu islands region, Japan, which was then characterized by Japan Meteorological Agency (JMA) as being the largest EQ swarm ever recorded [7].

For a time series comprising N events, which actually is a temporal point pattern [8], the natural time χ_k for the k-th event of energy Q_k is the quantity $\chi_k = k/N$ [9–11]. In particular, the time intervals between consecutive events is not considered, while their order is preserved. (For example, see fig. 1 of ref. [12] in which the upper graph depicts an EQ sequence in conventional time and the lower graph in natural time.) Then the analysis is carried out by studying the evolution of the pair (χ_k, p_k), where $p_k = Q_k/\sum_{n=1}^{N} Q_n$ is the normalized energy for the k-th event, and using the normalized power spectrum $\Pi(\omega) \equiv |\Phi(\omega)|^2$ (cf. ω stands for the angular natural frequency) defined by $\Phi(\omega) = \sum_{k=1}^{N} p_k \exp(i\omega\chi_k)$. $\Phi(\omega)$ is the characteristic function of p_k for all $\omega \in \mathcal{R}$, because p_k can be regarded as a probability for the occurrence of the k-th event at χ_k. $\Phi(\omega)$ is studied at $\omega \to 0$, since all the moments of the distribution of p_k can be estimated from the derivatives $\mathrm{d}^m\Phi(\omega)/\mathrm{d}\omega^m$ (for m positive integer) of the characteristic function $\Phi(\omega)$ at $\omega \to 0$. Considering

(a) E-mail: pvaro@otenet.gr (corresponding author)

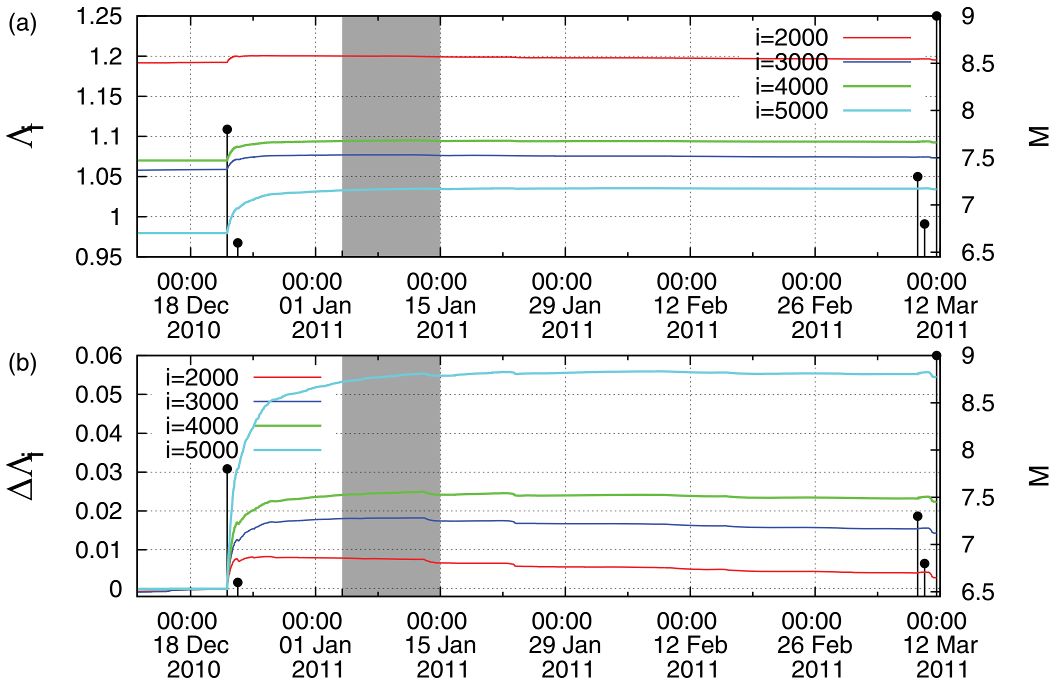

Fig. 1: The complexity measure Λ_i (a) and the change $\Delta\Lambda_i$ (b) from its value just before the M7.8 EQ on 22 December 2010 (with an epicenter at 27.05°N 143.94°E) *vs.* the conventional time almost two and a half months after this EQ. The $M \geq 6.5$ EQs are depicted with vertical lines ending at black solid circles read in the right scale. The gray shaded area shows the duration of the Earth's magnetic field variations [48].

the Taylor expansion $\Pi(\omega) = 1 - \kappa_1\omega^2 + \kappa_2\omega^4 + \ldots$, the quantity κ_1,

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

is defined, which becomes equal to 0.070 at the critical state for several dynamical systems studied [13–18]. This quantity, as shown by a careful study [19], may be considered as an order parameter of seismicity, see also ref. [20]. EQs exhibit complex correlations in time, space and magnitude (*e.g.*, refs. [21–26]). The occurrence of large EQs has been widely accepted [14,15,27,28] as likely associated with a critical point and κ_1 is a useful quantity in identifying the approach to a critical point.

In the 1980s, a criticality model [29] inspired the investigation of transient Earth's electric field signals before major EQs [30,31] (cf. a different model for the electrical precursors is given in ref. [32], a series of which is called Seismic Electric Signals (SES) activity [31]). The study of the SES physical properties may reveal the magnitude and the epicentral area of an impending EQ.

A SES activity (accompanied by anomalous variations of the magnetic field of the Earth [6,33,34] due to Maxwell equations) has a lead time [14] from a few weeks to $5\frac{1}{2}$ months before a strong EQ (cf. Rikitake [35] found that the lead time increases with magnitude), and its initiation almost coincides [36,37] with the minimum β_{min} of the fluctuations β of the order parameter κ_1 of seismicity [38]. These fluctuations are computed using a sliding window of length i by the detailed procedure described in ref. [38]. Such minima β_{min}, apart from being clear anomalies when compared to the statistics of the corresponding β time-series (see fig. 1 of ref. [37]), have been also shown [39] to be statistically significant EQ precursors with p-value of the order of 10^{-5} resulting to an area A under the curve in the receiver operating characteristics diagram equal to $A = 0.95$ [40].

The entropy S in natural time [41] is given by

$$S = \langle\chi\ln\chi\rangle - \langle\chi\rangle\ln\langle\chi\rangle, \quad (2)$$

where $\langle f(\chi)\rangle = \sum_{k=1}^{N} p_k f(\chi_k)$ stands for the average value of $f(\chi)$ weighted by p_k, *i.e.*, $\langle\chi\ln\chi\rangle = \sum_{k=1}^{N} p_k(k/N)\ln(k/N)$ and $\langle\chi\rangle = \sum_{k=1}^{N} p_k(k/N)$. Upon reversing the time arrow we obtain an entropy S_- different from S, thus there exists a change $\Delta S \equiv S - S_-$ in natural time under time reversal. In particular, upon considering [14,15,42] the time-reversal $\hat{T}$, *i.e.*, $\hat{T}p_k = p_{N-k+1}$, we get the entropy labelled by S_-, *i.e.*,

$$S_- = \sum_{k=1}^{N} p_{N-k+1}\frac{k}{N}\ln\left(\frac{k}{N}\right) - \left(\sum_{k=1}^{N} p_{N-k+1}\frac{k}{N}\right)\ln\left(\sum_{k=1}^{N} p_{N-k+1}\frac{k}{N}\right). \quad (3)$$

The calculation of ΔS is made through the whole time series by means of a sliding window of length i (= number

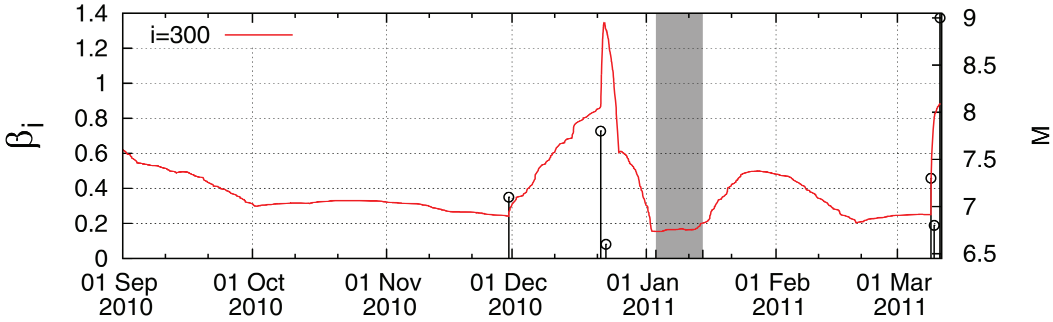

Fig. 2: The fluctuations β_i during almost six months for a sliding window of $i = 300$ consecutive events of the order parameter of seismicity *vs.* the conventional time. The gray shaded area shows the duration of the Earth's magnetic field variations recorded before the $M9.0$ Tohoku EQ [48].

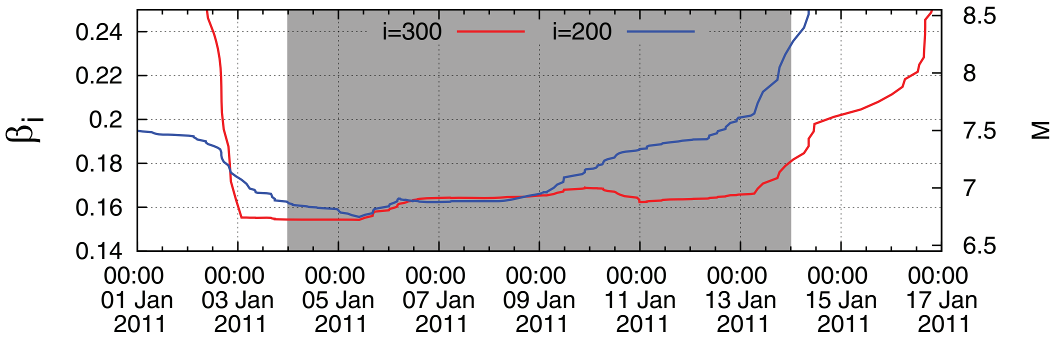

Fig. 3: The fluctuations β_i for the two scales $i = 200$ and 300 consecutive events of the order parameter of seismicity *vs.* the conventional time during almost the first two weeks of January 2011. As in fig. 2, the gray shaded area shows the duration of the Earth's magnetic field variations measured by Xu *et al.* [48].

of successive events), each time by one event. The entropies S_i and $(S_-)_i$, and therefrom their difference ΔS_i, are calculated each time and hence a new time series comprising consecutive ΔS_i values is obtained. As for the ΔS fluctuations they are also obtained by means of a window of length i mentioned above sliding through the EQ catalog. By means of the standard deviation $\sigma(\Delta S_i)$ of the time series of ΔS_i, the complexity measure Λ_i [14,15,43,44]

$$\Lambda_i = \frac{\sigma(\Delta S_i)}{\sigma(\Delta S_{100})}, \qquad (4)$$

is defined where the denominator corresponds [44] to the standard deviation $\sigma(\Delta S_{100})$ of the time series of ΔS_i with $i = 100$ events.

We now study the $M9.0$ Tohoku EQ using the JMA seismic catalogue [12,38] and considering all EQs of magnitude $M \geq 3.5$ (to assure data completeness) from 1984 until the Tohoku EQ occurrence on 11 March 2011 within the area N_{25}^{46} E_{125}^{148}. Since there exist 47204 EQs in the concerned period, we find an average of ~145 EQs/month. Concerning the selection of the proper scale i for the study of time evolution of ΔS_i we think as follows: A SES activity, whose lead time ranges from a few weeks up to around $5\frac{1}{2}$ months [14] exhibiting critical behavior [10,41,45], is observed during a period in which long range correlations prevail between EQ magnitudes. To the contrary, before the initiation of the SES activity, and hence before the minimum β_{min} observed [38] in the fluctuations of the order parameter κ_1 of seismicity, the temporal correlations between EQ magnitudes exhibit an anticorrelated behavior [46]. Hence, in order for this considerable change in the temporal correlations between EQ magnitudes before and just after the initiation of an SES activity to be captured by the time evolution of ΔS_i, we start our study of ΔS_i from the scale of the order of $i \sim 10^3$ events, which corresponds to the number of $M \geq 3.5$ EQs that occur during a period around the maximum lead time of SES activities.

In fig. 1 we plot the Λ_i values and their increase $\Delta\Lambda_i$ for the scales $i = 2000$, 3000, 4000, and 5000 events *vs.* the conventional time from 10 December 2010 until the occurrence of the $M9.0$ Tohoku EQ on 11 March 2011 (cf. in the relevant calculations we did not include the Tohoku mainshock). All $M \geq 6.5$ EQs are depicted in this figure with vertical lines ending at circles in the right scale. We observe that on 22 December 2010 an abrupt increase of Λ_i is evident upon the occurrence of a $M7.8$ EQ with an epicenter at 27.05°N 143.94°E. Upon the occurrence of this $M7.8$ EQ, we also showed [47] that upon analyzing in natural time all $M \geq 3.5$ EQs in an almost 27 year period in Japan from 1 January 1984 until the occurrence of the $M9.0$ Tohoku EQ on 11 March 2011, a pronounced

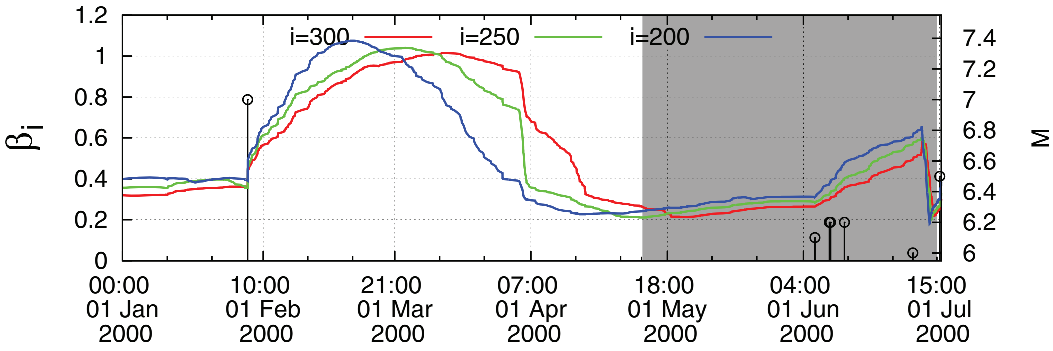

Fig. 4: The fluctuations β_i for the scales $i = 200$, 250 and 300 consecutive events decreased in the late April 2000 and increased (recovering) before the first $M6.5$ EQ on 1 July 2000 close to Niijima Island, Izu, Japan.

minimum (p-value equal to 3%) of ΔS_i was observed at scales like 4×10^3, 5×10^3 and 7×10^3 events while Λ_i became maximum, see ref. [15] and references therein. In addition it was also shown that this ΔS_i minimum is statistically significant upon changing either the EQ depth (from 0–300 km) or the magnitude threshold and occurs at the same date (22 December 2010) at which the exponent α resulting from the detrended fluctuation analysis of the EQ magnitude time series exhibits a minimum with a value ($\alpha \sim 0.35$) indicating anticorrelated behavior.

A closer inspection of fig. 1 reveals the following challenging result: The gray shaded area in fig. 1, which exhibits increased Λ_i values, extends from the beginning of January 2011 until around 14 January 2011, almost coincides with the period during which Xu *et al.* [48] recorded evident variations of the Earth's magnetic field, which as mentioned above —in accordance with the Maxwell equations— accompany an intense SES activity. Moreover, this almost coincides with that depicted in figs. 2 and 3, where the order parameter fluctuations minimize. It should be noted that these variations have been shown [49] to be anomalous and unique over a 16-year long period, *i.e.*, with p-value equal to 0.17%, and unlikely to be caused by geomagnetic storms. In other words the Λ_i (as well as the $\Delta\Lambda_i$) values corresponding to the shaded area in fig. 1 —that have been computed *solely* from the natural time analysis of seismicity data— appear during the same period with the detection of anomalous variations of the Earth's magnetic and/or electric field, *i.e.*, an SES activity. It is striking that two independent datasets (*i.e.*, seismicity, Earth's magnetic and electric field variations) appear almost simultaneously, see fig. 1.

The above findings have been also confirmed for the volcanic-seismic swarm activity in 2000 in the Izu island region, Japan, which is the largest volcanic-seismic swarm ever recorded in Japan. In this case, the Earth's electric field was recorded [36,50]. In particular, the Izu 2000 swarm activity was preceded by a pronounced electrical activity with innumerable signals [50] (accompanied by a ULF geomagnetic anomaly [51]) that started two months prior to the swarm onset. Specificaly, Uyeda *et al.* [52] reported that significant disturbances of the Earth's electric field started on Niijima Island (see their fig. 3) from late April 2000. Their investigation [50] was made for the period from the late April until just before the occurrence of the first magnitude 6 class EQ very close to Niijima Island (1 July 2000), see fig. 4.

Let us summarize: It was found that, in the light of the new concept of time termed natural time, evidence has been found that statistically significant anomalous changes appear simultaneously before major EQs in independent datasets of different geophysical observables (Earth's magnetic and/or electric field changes, increased fluctuations of the entropy of seismicity under time reversal —*i.e.*, increased Λ_i values— and decreased fluctuations of the order parameter of seismicity). The present results bring about the need of electromagnetic monitoting of EQ prone areas in order to identify and verify these precursory changes in future major EQs. Such a monitoring has already started in Greece since 1981 with encouraging results. For example, during the decade just after the introduction of natural time in 2001, five major EQs with $M_W \geq 6.4$ within the area $\mathrm{N}_{36}^{41}\mathrm{E}_{19}^{27}$ occurred, all of which have been preceded by evident SES activities that enabled the successful identification of their epicentral areas and magnitudes, see sects. 7.2 and 7.3 of ref. [14].

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