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Fluctuations of the entropy change under time reversal: Further investigations on identifying the occurrence time of an impending major earthquake

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Abstract – A procedure has been developed in a previous publication (SKORDAS E. S. *et al.*, *EPL*, **128** (2019) 49001) for the identification of the occurrence time of the Tohoku earthquake of magnitude $M = 9.0$ that occurred in Japan on 11 March 2011 based on natural time analysis of seismicity. Using the complexity measure that quantifies the fluctuations of the entropy change ΔS of seismicity under time reversal, we show here that, in the longer scales, the complexity measure of the entire Japanese region starts increasing from 22 December 2010 (the date at which ΔS is minimized) reaching a maximum close to the appearance of a Seismic Electric Signals activity (evidenced from the recording of anomalous magnetic field variations on the z-component) in the beginning of January 2011; then it gradually diminishes until just before the mega earthquake. On the other hand, around two days before its occurrence, the complexity measure in the candidate epicentral area exhibits an abrupt increase. This difference reveals, well in advance, that the $M7.3$ earthquake on 9 March 2011 was a foreshock.

Introduction. – It is widely accepted [1–3] that earthquakes (EQs), which exhibit complex correlations in time, space and magnitude (M) (*e.g.*, [4–11]), can be considered as critical phenomena, since the observed EQ scaling laws [12] indicate the existence of phenomena closely associated with the proximity of the system to a critical point. The order parameter of seismicity is the quantity by which one can identify the approach of the dynamical system to a critical point. The introduction of such a parameter for the case of seismicity, labeled hereafter κ_1, became possible after the suggestion of a new procedure for the analysis of complex time series, termed natural time analysis, which was introduced in the beginning of the 2000s (*e.g.*, see ref. [13]) and is summarized in the next section.

The Tohoku mega earthquake of magnitude 9.0 that occurred in Japan on 11 March 2011 devastated the Pacific side of northern Honshu with a huge tsunami causing more than 20000 victims and serious damage to the Fukushima nuclear plant. It is the largest magnitude event recorded in Japan and seismologists were shocked because it was not even considered possible that it might happen in the East Japan subduction zone. This mega earthquake was preceded by a $M7.3$ foreshock that occurred almost two days before. Upon the occurrence of this $M7.3$ EQ, seismologists could not identify that this was foreshock of a significantly larger EQ, which would be of paramount importance for practical purposes. It is one of the main goals of this paper to investigate whether such an identification was possible by means of the fluctuations of the entropy change ΔS under time reversal (*i.e.*, upon reversing the direction of the time arrow). We clarify that the concept of entropy S in natural time defined below is applicable to deterministic as well as stochastic processes. It is a dynamic entropy depending on the sequential order of events and is fundamentally different [14,15] from other entropies.

The quantity ΔS is a measure that may serve for the identification of when the system approaches the critical point (dynamic phase transition) [3]. As a first example, we mention that ΔS has been applied to identify the time of an impending sudden cardiac death (SD) [16], which is an important cause of mortality worldwide as well as to distinguish conjective heart failure patients from truly healthy humans [16–18] (cf. for the explanation of why SD maybe considered [14–16] as a phase transition see refs. [3,18]). As a second example, it has been shown [19] that upon analyzing in natural time (see below) the Olami-Feder-Christensen (OFC) model for EQs [20], a non-zero change ΔS is identified. This reveals a breaking of the time symmetry, thus reflecting the predictability in the OFC model, which is probably [21] the most studied non-conservative, supposedly, self-organized criticality model and appears to be closer to reality than others [22]. In particular, it was found that in the OFC model, ΔS exhibits a clear minimum [3] (or maximum if we define, *e.g.*, see ref. [19], $\Delta S \equiv S_- - S$ instead of $\Delta S \equiv S - S_-$, see below) before a large avalance, *i.e.*, a large EQ. Actually, by analyzing in natural time the seismicity, almost three months before the $M9$ Tohoku EQ, *i.e.*, on 22 December 2010, a statistically significant minimum ΔS_{min} of ΔS of seismicity in the entire Japanese region under time reversal was found in ref. [23]. Specifically, the probability to observe by chance such a deep (or even deeper) minimum was estimated [23] to be close to 3%, while the fact that it can be considered as a precursor to the $M9$ Tohoku EQ had a much smaller probability (<1%) to occur by chance as shown in ref. [24] when employing the recently introduced method of event coincidence analysis, see, *e.g.*, refs. [25,26].

Concerning this minimum of ΔS identified on 22 December 2010, on the same date a significant change in the temporal correlations of the EQ magnitude time series in Japan has been observed as follows: The magnitude time series before major EQs have been investigated in the entire Japanese region, *i.e.*, in the broad area 25°–46°N, 125°–148°E, during the period 1984–2011 in ref. [27] by employing the Detrended Fluctuation Analysis (DFA) [28] which has been established as a standard method to investigate long-range correlations in non-stationary time series in diverse fields (*e.g.*, [6,28–38]). For each target EQ, the magnitudes of $i = 300$ consecutive events before the target have been analyzed [27] and a DFA exponent was therefrom deduced, hereafter labeled α, where α =0.5 means random, α greater than 0.5 long-range correlation, and α less than 0.5 anti-correlation. Focusing on the $M9$ Tohoku EQ under discussion, these calculations [27] led to α values markedly smaller than 0.5 after around 16 December 2010, including an evident minimum, *i.e.*, $\alpha \approx 0.35$, on 22 December 2010. This was the lowest α value ever observed during this ~27 year period. From about the last week of December 2010 until around 8 January 2011, the α values indicate the establishment of long-range correlations since $\alpha > 0.5$. This period overlaps the observation [39–41] of anomalous magnetic field variations on the z-component from 4 to 10 January 2011 at two measuring sites —Esashi (ESA) and Mizusawa (MIZ), see fig. 1 of ref. [42]— lying at epicentral distances of around 130 km, which reflects the detection also of Seismic Electric Signals (SES) activity. SES are low-frequency transient changes of the electric field of the Earth preceding EQs [43] and several SES recorded within a short time are termed as SES activity [44] (with a lead time from a few weeks to around $5\frac{1}{2}$ months [3]). Major EQs are preceded by intense SES activities accompanied by evident Earth's magnetic field variations [45] mainly recorded on the z-component. The physical model for SES generation [43,46] suggests the following since in the Earth's crust electric dipoles always exist due to lattice imperfections in the ionic constituents of rocks: In the future focal region of an EQ, where the electric dipoles have initially random orientations, the stress σ starts to gradually increase due to an excess stress disturbance and when this gradually increasing stress reaches a critical value, σ_{cr}, the electric dipoles exhibit a cooperative orientation resulting in the emission of a transient SES. Such a cooperativity is a hallmark of criticality [47].

The present paper is structured as follows: In the next section, a short summary of natural time analysis is given, while the seismicity data along with the procedure followed in their analysis are described in the subsequent "Data and analysis" section. The results are then followed by a "Discussion" section. Finally, our main conclusions are summarized in the last section.

Natural time analysis and the entropy change fluctuations under time reversal. – For a time series comprising N events, we define an index for the occurrence of the k-th event by $\chi_k = k/N$, which we term natural time. We, then, study the pairs (χ_k, Q_k), or the pairs (χ_k, p_k), where Q_k is the energy and $p_k = Q_k / \sum_{n=1}^{N} Q_n$ the normalized energy for the k-th event [3,13,48]. Natural time is currently considered as the basis for a new method for estimating the seismic risk by Turcotte and coworkers [49–52].

The variance of χ weighted for p_k, labeled κ_1, which can be considered [53] as an order parameter for seismicity (a mainshock is the new phase), is given by [3,13,53,54] $\kappa_1 = \sum_{k=1}^{N} p_k(\chi_k)^2 - (\sum_{k=1}^{N} p_k \chi_k)^2$.

The entropy S in natural time defined in ref. [55] is

$$S = \langle \chi \ln \chi \rangle - \langle \chi \rangle \ln \langle \chi \rangle, \tag{1}$$

where $\langle f(\chi) \rangle = \sum_{k=1}^{N} p_k f(\chi_k)$ denotes the average value of $f(\chi)$ weighted by p_k, *i.e.*, $\langle \chi \ln_\chi \rangle = \sum_{k=1}^{N} p_k \cdot (k/N) \ln(k/N)$ and $\langle \chi \rangle = \sum_{k=1}^{N} p_k (k/N)$. The entropy obtained by eq. (1) upon considering [3,56] the time reversal $\hat{T}$, *i.e.*, $\hat{T} p_k = p_{N-k+1}$, is labelled by S_-, *i.e.*,

$$\begin{aligned} S_- = &\sum_{k=1}^{N} p_{N-k+1} \frac{k}{N} \ln\left(\frac{k}{N}\right) \\ &- \left(\sum_{k=1}^{N} p_{N-k+1} \frac{k}{N}\right) \ln\left(\sum_{k=1}^{N} p_{N-k+1} \frac{k}{N}\right). \end{aligned} \tag{2}$$

S_- is different from S, thus there exists a change $\Delta S \equiv S - S_-$ in natural time under time reversal. Hence, S does satisfy the condition to be time-reversal asymmetric [3,16,56]. Using a natural time window of length i sliding, event by event, through the time series of L consecutive events the entropy in natural time is determined for each position $j = 1, 2, \ldots, L-i$ of the sliding window, thus, a time series of S_i is constructed [16]. We also construct the time series of $(S_-)_i$ by employing eq. (2). Computing the standard deviation $\sigma(\Delta S_i)$ of the time series of $\Delta S_i \equiv S_i - (S_-)_i$, the complexity measure Λ_i is defined by [3,17]

$$\Lambda_i = \frac{\sigma(\Delta S_i)}{\sigma(\Delta S_{100})}, \tag{3}$$

where the denominator stands for the standard deviation $\sigma(\Delta S_{100})$ of the time series of ΔS_i of $i = 100$ events (the selection of a different scale in the denominator, *e.g.*, $i = 50$ or 200 events, instead of $i = 100$ events, see fig. S1 in the Supplementary Material `Supplementarymaterial.pdf` (SM) that will be discussed later, would change of course the numerical values obtained but the whole behavior and physical picture of the results concerning the time evolution of Λ_i would remain the same). In other words, Λ_i quantifies how the statistics of ΔS_i time series varies upon changing the scale from 100 to another scale i, the physical meaning of which is of profound importance for the study of the dynamical evolution of a complex system (see p. 159 of ref. [3]).

Data and analysis. – Q_k, and hence p_k, for EQs is estimated through the usual relation [57]: $\log_{10}(E) = 1.5M_w + 4.8$ for the seismic energy E in Joules as a function of the moment magnitude M_w leading to $Q_k \propto 10^{1.5M_k}$. Here, as in refs. [58,59], we used the EQ catalog of the Japan Meteorological Agency (JMA) for $M_{JMA} \geq M_{thres}$ with magnitude threshold $M_{thres} = 3.5$ and in order to obtain Q_k we coverted the reported magnitude M_{JMA} to M_w according to the formulae suggested in ref. [60]. When we use the symbol M we refer to M_{JMA}. For reasons explained in ref. [42], the time evolution of ΔS_i is focused on scales of the order of $i \sim 10^3$ events, which is crucial —as discussed in ref. [54]— because this scale corresponds to the number of seismic events $M \geq 3.5$ that occur during a period of at least around the maximum lead time of SES activities (since we have ∼145 EQs per month in the entire Japanese region and a period of at least $5\frac{1}{2}$ months).

Results. – The following general feature was found in ref. [42], where we analyzed the seismic data in the entire region of Japan ($M \geq 3.5$) in natural time and calculated the complexity measure Λ_i. For each of the scales that are markedly longer than 2000 events, *e.g.*, $i = 3000$, 4000 and 5000 events, the dates show a tendency to be clearly clustered into two groups: The one group that comprises markedly larger Λ_i values corresponding to dates later than the date 22 December 2010 at which ΔS_{min} has been observed, thus being closer to the occurrence date of the Tohoku EQ. The other group comprises appreciably lower Λ_i values corresponding to earlier dates. Practically the same behavior is observed upon increasing the magnitude threshold to 4.0, *i.e.*, by considering only the $M \geq 4.0$ EQs in our computations, and using scales that are smaller by a factor of 2.5 in view of the smaller number of EQs per month we have for this threshold (cf. see fig. S6 of ref. [23]).

Here, we proceed to a more detailed investigation of the Λ_i values and find that their time evolution in the entire Japanese region is distinctly different from that in the future epicentral area. This difference is of major importance since it reveals that the M7.3 EQ on 9 March was a foreshock.

Focusing on the results obtained when considering all $M \geq 3.5$ EQs in the entire Japanese region, we find that they depend on whether we start the computation appreciably earlier in the past. This reflects that for each scale a smaller percentage of the events is entered into the Λ_i calculation, thus fewer events are close to the mainshock occurrence. The calculation here, is made for the same 10 dates mentioned in ref. [42] except one, *i.e.*, by replacing the date 8 March 2011 (at 00:00 LT) with the date 11 March 2011 (at 00:00 LT) which is closer to the mega earthquake. They are given in the caption of fig. 1, which depicts the results when starting the computation for $M \geq 3.5$ EQs on either 1 January 2010 (fig. 1(a)) or four years earlier, *i.e.*, on 1 January 2006 (fig. 1(b)). A close inspection of fig. 1(a) shows that for each scale longer than ≈2000 events, the Λ_i values after 1 January 2011, which is a date very close to the initiation of the SES activity (thus long-range temporal correlations develop, as mentioned) reach a maximum and afterwards exhibit a systematic decrease until the mainshock occurrence. This systematic behavior (which is robust since it is not affected if we change the scale in the denominator in eq. (3) from $i = 100$ events to $i = 50$ or 200 events, see fig. S1 in the SM), however, is lost in the longer scales in fig. 1(b) where for $M \geq 3.5$ we start the calculation on 1 January 2006. In other words, this dictates that when starting the computation closer to the impending mainshock, the Λ_i values maximize and afterwards upon approaching the date of the SES activity start to systematically diminish as we move closer to the mainshock occurrence. The same behavior is observed in fig. 2(a) for $M \geq 4.0$ EQs, where we started the computation on 1 January 2010, while this behavior is lost in fig. 2(b) when starting the calculation in 2006. This behavior persists if we start the computation even closer to the mainshock, *i.e.*, on 1 March 2010, or 1 May 2010, or 1 July 2010 (instead of 1 January 2010), see fig. 3 for $M \geq 3.5$ EQs. In this figure, it can be clearly visualized that the Λ_i values gradually decrease as we move closer to the mega earthquake occurrence. On the other hand, studying the results obtained from the calculation of the Λ_i values computed from EQs in the candidate epicentral region, see fig. 1 of ref. [42] (which has been estimated by means of a spatiotemporal study of the order parameter fluctuations of seismicity developed

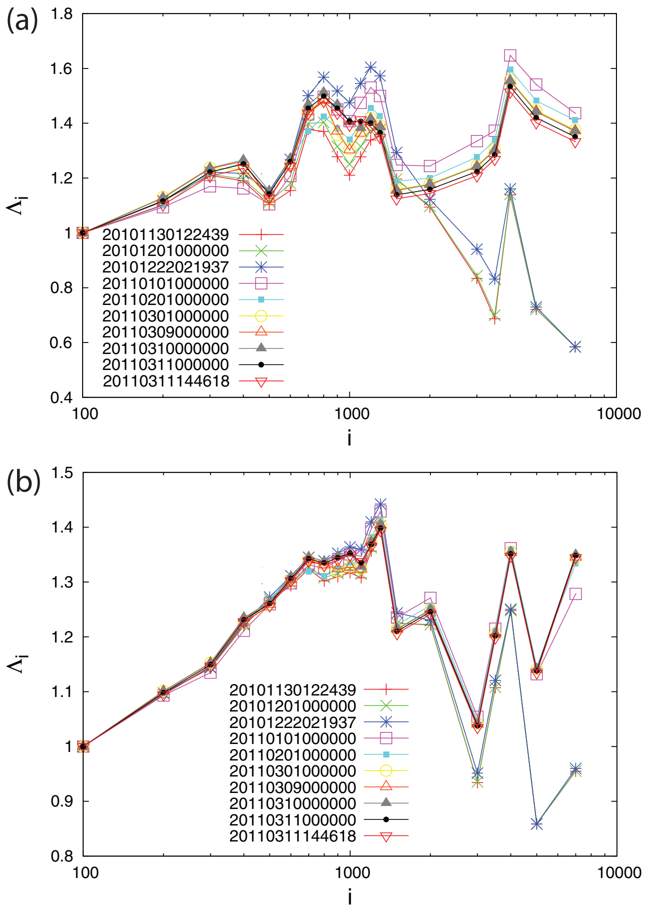

Fig. 1: Plot of Λ_i values *vs.* the scale i (number of events) for all $M \geq 3.5$ EQs in the entire Japanese region $N_{25}^{46}E_{125}^{148}$ since 1 January 2010 (a) and 1 January 2006 (b). The Λ_i values have been calculated for each scale at the following dates: 30 November 2010 (pluses in red, just before the $M7.1$ EQ on this date), 1 December 2010 (crosses in green), 22 December 2010 (asterisks in blue, just before the $M7.8$ EQ that occurred on this date), 1 January 2011 (open squares in magenta), 1 February 2011 (solid circles in cyan), 1 March 2011 (open circles in brown), 9 March 2011 (open triangles in orange, at 00:00 LT, thus almost 12 hours before the $M7.3$ EQ occurrence on 9 March 2011), 10 March 2011 (gray filled triangles, at 00:00 LT thus almost 12 hours after the $M7.3$ EQ occurrence on 9 March 2011), 11 March 2011 (solid circles in black, at 00:00 LT, thus almost 15 hours before the mega earthquake occurrence) and 11 March (inverted red triangles, almost 10 min before the $M9$ Tohoku EQ occurrence). The time format in the figure keys is YYYYMMDDhhmmss in Japan Standard Time.

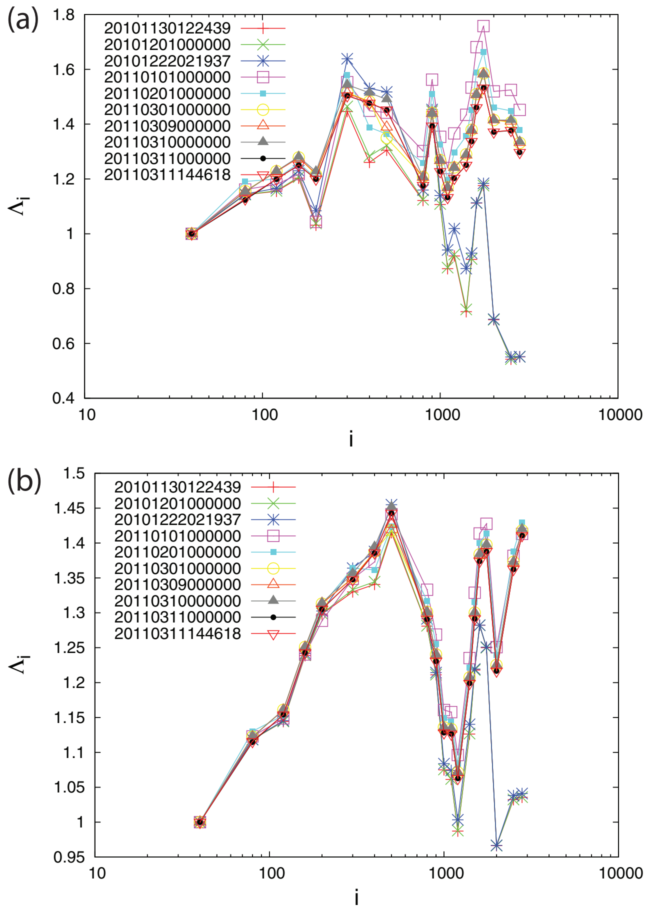

Fig. 2: The same as fig. 1, but here we plot the Λ_i values *vs.* the scale i by condidering only the $M \geq 4.0$ EQs.

in ref. [59] and summarized in ref. [42]), we find (see fig. 5 of ref. [42]) that irrespective of the year at which we start the computation (*i.e.*, by starting the computation since 1 January 2006, 1 January 2008, 1 January 2009, and 1 January 2010, thus roughly five, three, two and one years before the $M9.0$ Tohoku EQ occurrence), for each of the scales longer than around $i = 400$–500 events the behavior is more or less the same as follows: All the resulting Λ_i values almost coincide, but after the $M7.3$ EQ on 9 March 2011, they exhibit an increase followed by a further increase until 10 min before the occurrence of the mega earthquake on 11 March 2011.

Discussion. – In figs. 4(a), (b) we plot the Λ_i values at several dates during the last week of December 2010 and the first week of January 2011 to show that, for each scale, they maximize after exhibiting an increase from their minimum value on 22 December 2010 when we recall that ΔS_{min} appeared. This could be understood in the following context.

The experimental results show that three phenomena appeared around the beginning of January 2011: Beyond the observation of an SES activity initiation, two more phenomena appear almost simultaneously, the establishment of long-range temporal correlations between earthquake magnitudes and the deepest minimum β_{min} (during the period from 1 January 1984 until the $M9$ Tohoku EQ occurrence) of the fluctuations β of the order parameter κ_1 of seismicity on 5 January 2011 [58]. The latter agrees with the experimental finding that the fluctuations of the order parameter κ_1 of seismicity have been observed [61,62] to exhibit a minimum β_{min} when an SES activity starts. Recall that this simultaneous appearance

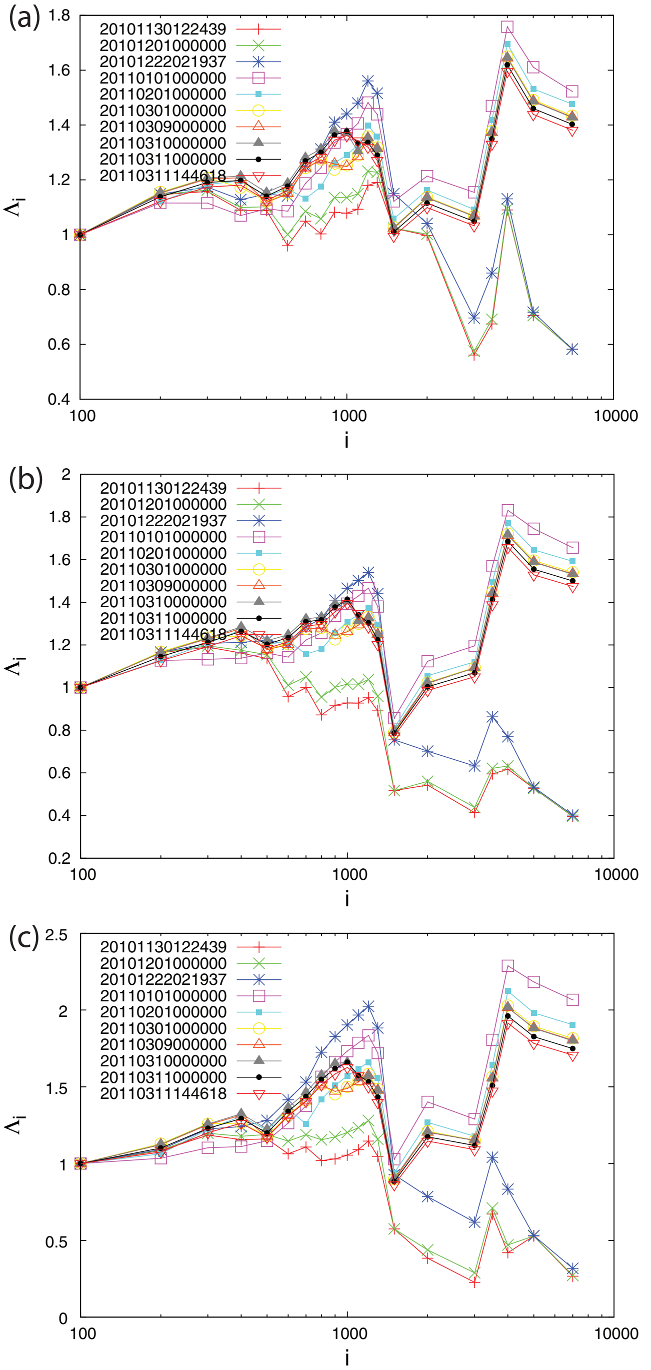

Fig. 3: The same as fig. 1, but here we plot the Λ_i values *vs.* the scale i when starting their computation since 1 March 2010 (a), 1 May 2010 (b) and 1 July 2010 (c) by condidering all $M \geq 3.5$ EQs.

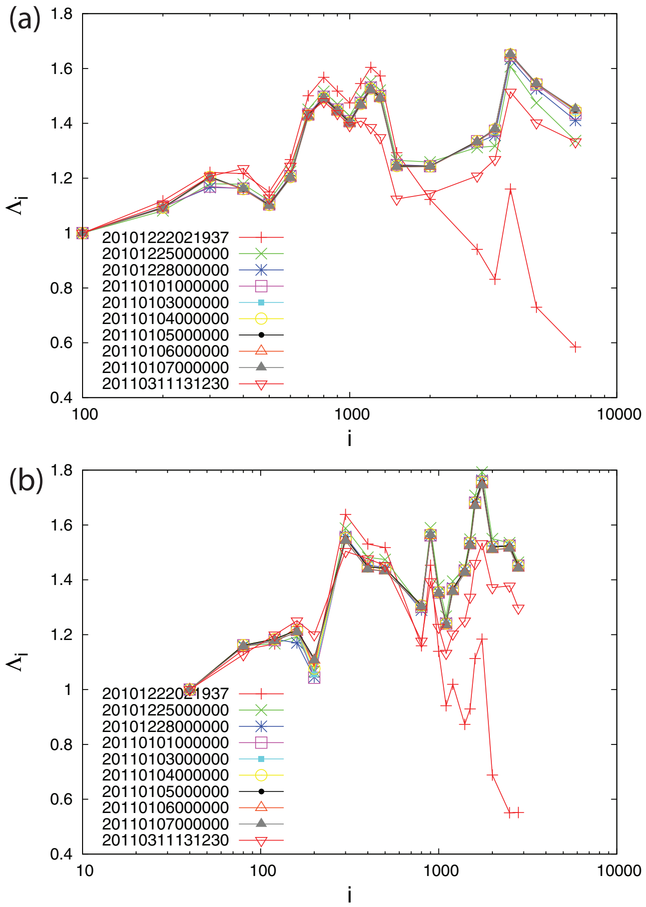

Fig. 4: The same as fig. 1, but here we calculate Λ_i values at several dates during the last week of December 2010 and the first week of January 2011 written in the inset by considering only the $M \geq 3.5$ EQs (a) and $M \geq 4.0$ EQs (b) in the entire Japanese region $\mathrm{N}_{25}^{46}\mathrm{E}_{125}^{148}$ since 1 January 2010.

of the three phenomena around 5 January 2011 has been preceded by a stage of an evident anti-correlated behavior between earthquake magnitudes since it was found that, as mentioned in the introduction, $\alpha = 0.35$ upon the occurrence on 22 December 2010 of the $M7.8$ EQ in southern Japan at 27.05°N 143.94°E. On this date the horizontal GPS azimuths, which were initially random, started to become gradually oriented toward the southern direction probably due to an excess stress disturbance. This corresponds to the first stage of the physical model for the SES generation (discussed in detail in ref. [62]) according to which upon an excess stress disturbance, the stress σ begins to increase until reaching σ_{cr} where the electric dipoles in the future focal area cooperatively orientate. Then, observations show the most intense crust uplift [62]. After the occurrence of β_{min} at around 5 January 2011, the orientations of GPS azimuths returned [63] to random around 13 January 2011, thus agreeing with the DFA exponent $\alpha = 0.5$ [27].

The behavior turned to anti-correlation around 23 January 2011 with DFA exponent $\alpha_{min} = 0.42$ and a shift of earthquake-related stress disturbance was observed [63] where westward movements replaced the southward ones, *i.e.*, the orientations of the residual displacements were re-aligned along the western direction and the crust depressed. After this change on 23 January 2011 the stress disturbance gradually approached the threshold of the fault rupture, and the orientations of the residual surface

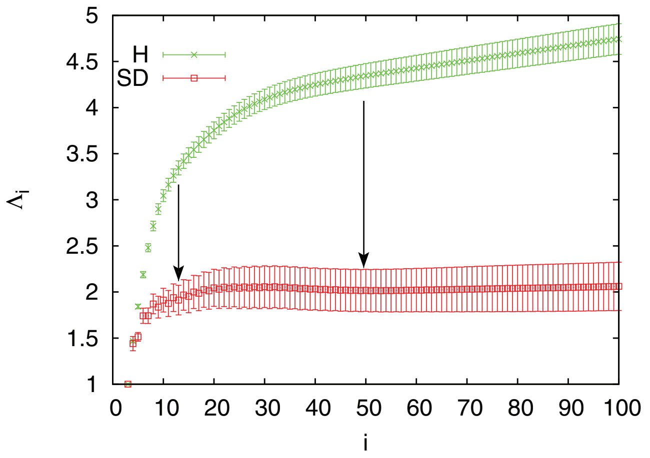

Fig. 5: Plot of Λ_i values *vs.* the scale i (number of heartbeats) for two classes of humans: healthy individuals (H) in the upper curve (green) and sudden cardiac death individuals (SD) in the lower curve (red) (for the data and their analysis in natural time see ref. [17]). The mean value for each scale and class together with the standard error are shown. The arrows mark the optimum scales 13 and 49 heartbeats respectively by means of which we may either specify [16] the initiation of the ventricular (V) fibrillation (F) onset (VF initiation remains one of the leading immediate causes of sudden cardiac death) or distinguish truly healthy humans from sudden cardiac death individulas [16,17].

displacements became random again [63] in agreement with the DFA exponent of the earthquake magnitude time series being close to 0.5 until around 10 February 2011 (see fig. 5 of ref. [27]), which indicates random behavior.

This fact that the Tohoku EQ occurred after the emergence of an almost random behavior is strikingly reminiscent of similar findings in other complex time series as follows: In the case of electrocardiograms (ECGs), for example, the long-range temporal correlations that characterize the healthy (H) heart rate variability break down for individuals at high risk of sudden cardiac death (SD), and this is often accompanied by emergence of uncorrelated randomness [3,36] (recall that SD could be viewed as a critical phenomenon, *e.g.*, see [14–16]). In other words, this can be seen as follows: When plotting the Λ_i values for H they exceed considerably those for SD, see fig. 5. Hence, our experimental finding here that in the longer scales the Λ_i values after maximizing around the beginning of January 2011 start to gradually diminish until almost 10 min before the $M9$ Tohoku EQ occurrence is consistent with the behavior observed in other complex systems, where by means of natural time analysis we have assured that for ECGs, for example, the high Λ_i values of healthy individuals (originated from long-range temporal correlations identified in ECG) fall into appreciably smaller Λ_i values in individuals of sudden cardiac death risk.

Summary and conclusions. – Analyzing in natural time the seismic data in the entire Japanese region and calculating the complexity measure Λ_i that quantifies the fluctuations of the entropy change ΔS under time reversal, the following results have been obtained for each of the longer scales i: Λ_i increases from 22 December 2010, where ΔS exhibited a minimum, and reaches a maximum value around the beginning of January close to the initiation of an intense SES activity evidenced from the recording of anomalous magnetic field variations mainly on the z-component (during which long-range correlations between EQ magnitudes have been ascertained). Subsequently, Λ_i gradually diminishes until the $M9$ Tohoku EQ occurrence on 11 March 2011. Such a behavior is strikingly reminiscent of similar findings in other complex time series, as in the case of electrocardiograms, in which long-range temporal correlations that have been found to characterize the healthy heart rate variability breakdown for individuals at high risk of sudden cardiac death.

Λ_i of the seismicity in the candidate epicentral area exhibits a different behavior showing an abrupt increase after the $M7.3$ EQ occurrence on 9 March 2011 up to the $M9$ EQ occurrence.

The fact that, upon the occurrence of the $M7.3$ EQ on 9 March, the Λ_i of the seismicity in the epicentral area showed an evident increase, while Λ_i in the entire Japanese region continued diminishing constitutes the key difference emerged from natural time analysis pointing to the characterization of the $M7.3$ EQ as a foreshock well in advance.

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