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Scale-specific order parameter fluctuations of seismicity in natural time before mainshocks

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Abstract – We have previously shown that the probability distribution of the order parameter κ_1 of seismicity in natural time turns to be bimodal when approaching a mainshock. This reflects that, for various natural time window lengths ending at a given mainshock, the fluctuations of κ_1 considerably increase for smaller lengths, *i.e.*, upon approaching a mainshock. Here, as a second step, we investigate the order parameter fluctuations, but when considering a natural time window of a fixed-length sliding through a seismic catalog. We find that when this length becomes comparable with the lead time of Seismic Electric Signals activities (*i.e.*, of the order of a few months), the fluctuations exhibit a global minimum before the strongest mainshock. Thus, the approach of the latter is characterized by *two* distinct features of the order parameter fluctuations that complement each other.

Introduction. – In the investigation of time series associated with complex systems, the following two types of complexity measures are usually involved: Scale-specific and scale-independent measures. For example, let us consider the study of the correlation properties of heartbeat fluctuations using scale-specific variance (root-mean-square fluctuations), σ, which is a scale-specific measure, and scaling (correlation) exponent, α, which is scale-independent, as measures of healthy (H) and cardiac impaired individuals. Upon employing two recent well-established methods, *i.e.*, Detrended Fluctuation Analysis [1–3] and Multiresolution Wavelet Analysis (see ref. [4] and references therein), the following results have been obtained [5]: First, the variance and the scaling exponent are uncorrelated. Second, the variance measure at *certain* scales is well suited to separate H from heart patients. However, for mortality predictions for myocardiac infarct group, the scaling exponents outperform the variance measure. Hence, in other words, it has been concluded [5] that the α and σ measures characterize the interbeat interval series in different ways: the variance, which is a measure in the time domain performs better as a diagnostic tool, while the scaling exponent, which is a measure in the frequency domain performs better as a prediction tool.

When employing natural time analysis [6], that uncovers unique dynamic features hidden behind the time series of complex systems, it has been found [7] (see also ref. [6] and references therein), that complexity measures that employ fluctuations on fixed time scales, seem to *complement* those measures that take into account fluctuations on different time scales. For example, when analyzing electrocardiograms in natural time aiming at the distinction between sudden cardiac death individuals (SD) and H, we make use of the entropy fluctuations and the aforementioned *complementarity* holds in the following sense [7] (see also pp. 410–413 of ref. [6]): if in the frame of the latter complexity measures (*i.e.*, different natural time scales) an ambiguity emerges in the distinction between SD and H, the former complexity measures (*i.e.*, fixed natural time scales) give a clear answer.

The evolution of seismicity is another example of complex time series. Earthquakes exhibit complex correlations in time, space and magnitude. This has been the objective of a number of recent studies [8–19]. The opinion prevails (*e.g.*, see ref. [12] and references therein) that the observed earthquake scaling laws [20,21] indicate the existence of phenomena closely associated with the proximity of the system to a *critical* point. Making use of the order parameter κ_1 of seismicity defined in natural time (see below), in a previous study [22] we investigated

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the period before and after a significant mainshock. Time-series for various lengths of W earthquakes that occurred before or after the mainshock have been studied. The natural time analysis of these time series revealed the following challenging finding: The probability distribution function $P(\kappa_1)$ *vs.* κ_1 exhibits a bimodal feature when approaching a mainshock. In an attempt to quantify this feature, we considered the *variability* of κ_1, which is just the ratio $\beta \equiv \sigma(\kappa_1)/\mu(\kappa_1)$ where $\sigma(\kappa_1)$ and $\mu(\kappa_1)$ stand for the standard deviation and the mean value for κ_1 (see also below). The bimodal feature reflects that upon approaching the mainshock with the number W of the earthquakes before mainshock decreasing, the variability of κ_1 should increase. This was strikingly confirmed several months after the appearance of ref. [22], since before the occurrence of the M9.0 devastating earthquake in Japan on March 11, 2011, the variability of κ_1 exhibited [23] a dramatic increase.

It is the scope of this paper to extend the study of ref. [22] based on the following grounds: Since in ref. [22], we analyzed time series for various lengths of W earthquakes before the mainshock, here we focus on the *complementary* case, *i.e.*, we consider a natural time window of fixed length (that means comprising a fixed constant number W of consecutive seismic events) which is sliding through the seismic catalog. In particular, we find here that the results become exciting upon using a crucial scale, *i.e.*, when these W consecutive events extend to a time period comparable to the lead time [6,24,25] of the precursory Seismic Electric Signals (SES) activities. The motivation to focus on that scale will become clear below after presenting first some background information on natural time analysis and SES activities.

Natural time analysis. Seismic Electric Signals. Background. – For a time series comprising N events we define [26,27] the natural time for the occurrence of the k-th event by $\chi_k = k/N$. Thus, we ignore the time intervals between consecutive events, but preserve their order and energy Q_k. We then study the evolution of the pair (χ_k, Q_k) where $p_k = Q_k/\sum_{n=1}^{N} Q_n$ is the normalized energy released during the k-th event. In this analysis, the approach of a dynamical system to criticality is identified by means of the variance [6,26–28] $\kappa_1 (\equiv \langle \chi^2 \rangle - \langle \chi \rangle^2)$ of natural time weighted for p_k where $\langle f(\chi) \rangle = \sum_{n=1}^{N} p_k f(\chi_k)$. We clarify that in this analysis, in a time series comprising N events (say earthquakes), upon the occurrence of an additional event, χ_k is "rescaled" as natural time changes to $\chi_k = k/(N+1)$ together with rescaling $p_k = Q_k/\sum_{n=1}^{N+1} Q_n$ and hence the quantity κ_1, which can be rewritten as

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

also changes.

Seismic Electric Signals activities are series [24,25] of low-frequency ($\leqslant 1$ Hz) electric signals that precede [6,29] major earthquakes. The generation mechanism [25,30] of SES is based on the widely accepted concept that the stress gradually increases in the future focal region of an earthquake. When this stress reaches a *critical* value σ_{cr}, a cooperative (re)orientation of the electric dipoles (which anyhow exist in the focal area due to lattice imperfections in the rocks) is attained, which leads to the emission of a transient electric signal which constitutes an SES. (The detection of several SES within a short time is termed SES activity.) The validity of this generation mechanism is strengthened by the fact that the SES activities (along with the associated magnetic field variations) exhibit *critical* dynamics since they are characterized by infinitely ranged temporal correlations [31].

In the frame of natural time analysis it has been suggested [28], as mentioned above, that the order parameter of seismicity is the quantity κ_1. The κ_1 value itself may lead to the determination of the occurrence time of the impending mainshock [6,26,32–34] in cases when SES data are available. In particular, when the κ_1 value resulting from the natural time analysis of the seismicity subsequent to the SES recording becomes approximately equal to 0.070, the mainshock occurs within a time window of the order of one week. (The condition $\kappa_1 = 0.070$ for the approach to criticality was originally theoretically obtained for SES activities [26,27] and recently [6,35] for a variety of other dynamical systems.) For example, this was the case for the mainshock of local magnitude $M_L(ATH) = 6.5$, reported from the Geodynamical Institute of the National Observatory of Athens (GI-NOA), that occurred on June 8, 2008, in western Peloponnese in Greece. Specifically, on May 29, 2008 we reported [36] that the κ_1 value of the seismicity calculated after the initiation of the SES activity (recorded from February 29, 2008 to March 2, 2008 at the station PIR located in western Greece) approached the value $\kappa_1 \approx 0.070$ and then the mainshock followed. In cases of the lack of SES data, we do not know from which seismic event we should start the natural time analysis of seismicity in order to compute the κ_1 value. Thus, we have to solely rely on the fluctuations of the order parameter [22] (see below).

The motivation for the selection of a specific natural time window scale. – We think along the following lines based on the knowledge accumulated from the 30 year observation of SES data:

First, we consider that observations of SES activities in Japan [37,38] in 2000s as well as in Mexico (see ref. [39] and references therein) and in California (see refs. [40,41] where magnetic field variations similar to those associated with the SES activities in Greece have been reported) have shown that their lead time is of the order of a few months, in agreement with earlier observations in Greece [6,24,25].

Second, according to the aforementioned SES generation mechanism, the SES observation marks when the system enters a critical stage and infinitely ranged long-range correlations develop (cooperative orientation of dipoles).

Thus, the SES observations in various countries reveal that before the occurrence of major earthquakes there is a crucial time scale of around a few months in which long-range correlations are developed or at least they are seriously affected. In other words, the SES observations dictate that a few months before a mainshock the critical stress σ_{cr} is attained, which may reflect that changes in the correlation properties of other associated physical quantities like seismicity or crustal deformation orientation may become detectable at that time scale *if* studying the corresponding order parameter fluctuations in natural time that enables the distinction of similar looking signals emitted from systems of different dynamics [7]. Specifically, here we study the extent to which this may affect the correlation properties of seismicity by focusing on the fluctuations of its order parameter κ_1 at this time scale.

The procedure followed. Data analysis. – We apply the following procedure: Let us take a natural time window length comprising $W(\gtrsim 10^2)$ consecutive events. Starting from the first earthquake, we calculate the κ_1 values using say $N = 6$ to 40 consecutive events. We next turn to the second earthquake, and repeat the calculation of κ_1. After sliding, event by event, through the whole natural time window, the computed values enable the calculation of the average value $\mu(\kappa_1)$ and the standard deviation $\sigma(\kappa_1)$ that correspond to this natural time window of length W. We then determine the variability of κ_1, *i.e.*, the quantity $\beta = \sigma(\kappa_1)/\mu(\kappa_1)$.

In order to simplify the calculation of the variability β of κ_1 for various windows W, for each earthquake e_i in the seismic catalog, we calculated the κ_1 values resulting when using the *previous* 6 to 40 consecutive earthquakes. Then, the hitherto obtained κ_1 values for the earthquakes e_{i-W+1} to e_i were considered for the estimation of the variability β for a natural time window length W. The resulting β value, labeled β_i, was attributed to e_i, the data of which was obviously *not included* in the β_i estimation.

The following two seismic catalogs have been used: First, the United States Geological Survey Northern California Seismic Network catalog available from the Northern California Earthquake Data Center, at the http address: `www.ncedc.org/ncedc/catalog-search.html`, hereafter called NCEDC. The earthquake magnitudes reported in this catalog are labeled with M. Second, the Greek seismic catalog of GI-NOA in which local magnitudes $M_L(ATH)$ are reported. The seismic moment, which is proportional to the energy release during an earthquake and hence to the quantity Q_k used in natural time analysis, is calculated as follows [6]: In the former catalog we used the relation $\log_{10}(M_0) = 1.5M + \text{const}$. In the Greek catalog, M_0 was estimated from the relation [42] $\log_{10}(M_0) = 1.5M_w + \text{const}$ by using $M_w = 1.09M_L(ATH) - 0.21$, *i.e.*, the least-squares fit proposed in ref. [43]. In short, for the latter catalog, the relation $\log_{10}(M_0) = 1.64M_L(ATH) + \text{const}$ has been used.

Results. – We first focus on the case of California. We consider all earthquakes reported by NCEDC (*i.e.*, within the area $N_{31.7}^{45.7}W_{127.5}^{112.1}$) during the 25 year period from January 1, 1979 to January 1, 2004. These data have been analyzed in natural time. It comprises 31832 earthquakes with $M \geqslant 2.5$, thus we have on average $\sim 10^2$ earthquakes per month. Thus, the lead time of SES activities, which is around a few months, say 2 months, with an upper limit [6] of around 5 months, corresponds to W values lying in the range from $W = 200$ to $W = 500$ events. Hence, hereafter we focus on such window lengths, *i.e.*, $W = 200$ to 500. For example, fig. 1(a) depicts the results for $W = 300$ of the variability of κ_1 *vs.* the number of events (earthquakes) during the aforementioned 25 year period. The same results for the variability of κ_1 are plotted in fig. 1(b) *vs.* the conventional time. An inspection of figs. 1(a), (b) reveals that before the strongest earthquake, which is the Landers earthquake that occurred on June 28, 1992, with $M = 7.4$, a transient change of the κ_1 variability is observed, which exhibits the *lowest value* (around 0.38) during the 25 year period investigated. We emphasize that *such a minimum value solely stems from earlier earthquakes.* To better visualize what happened before this strongest earthquake, fig. 1(c) shows in an expanded time scale, the variability of κ_1 during the 14 month period from May 1, 1991 to July 1, 1992. Putting aside the details, a close inspection of this figure shows that the lowest value of the κ_1 variability was observed around the period from the last days of January to the first days of February 1992. The $M7.4$ earthquake occurred somewhat less than five months later.

We now turn to the seismicity in Greece and consider all the earthquakes within the area $N_{34.0}^{39.5}E_{19.5}^{25.0}$ during the 10 year period from January 1, 1999 to December 31, 2008. By setting a magnitude threshold $M_L(ATH) \geqslant 3.2$ to assure data completeness, the GI-NOA catalog comprises 13287 earthquakes thus, we have on the average $\sim 10^2$ earthquakes per month as in the aforementioned case of California. By the same token, fig. 2(a) depicts the results, for $W = 300$, of the variability of κ_1 *vs.* the number of events (earthquakes) during the 10 year period 1999–2008. The same results of the variability of κ_1 are plotted *vs.* the conventional time in fig. 2(b). The earthquake with the largest $M_L(ATH)$ value of this period occurred on June 8, 2008 in western Peloponnese with $M_L(ATH) = 6.5$ already mentioned. An inspection of figs. 2(a) and 2(b), reveals that before this earthquake the *lowest value* of the κ_1 variability is observed. In order to better visualize what happened before this earthquake, fig. 2(c) shows, in an expanded scale, the variability of κ_1 *vs.* the conventional time during an almost three month period, *i.e.*, from the first week of March 2008 until its occurrence on June 8, 2008. We observe that after around the second week of

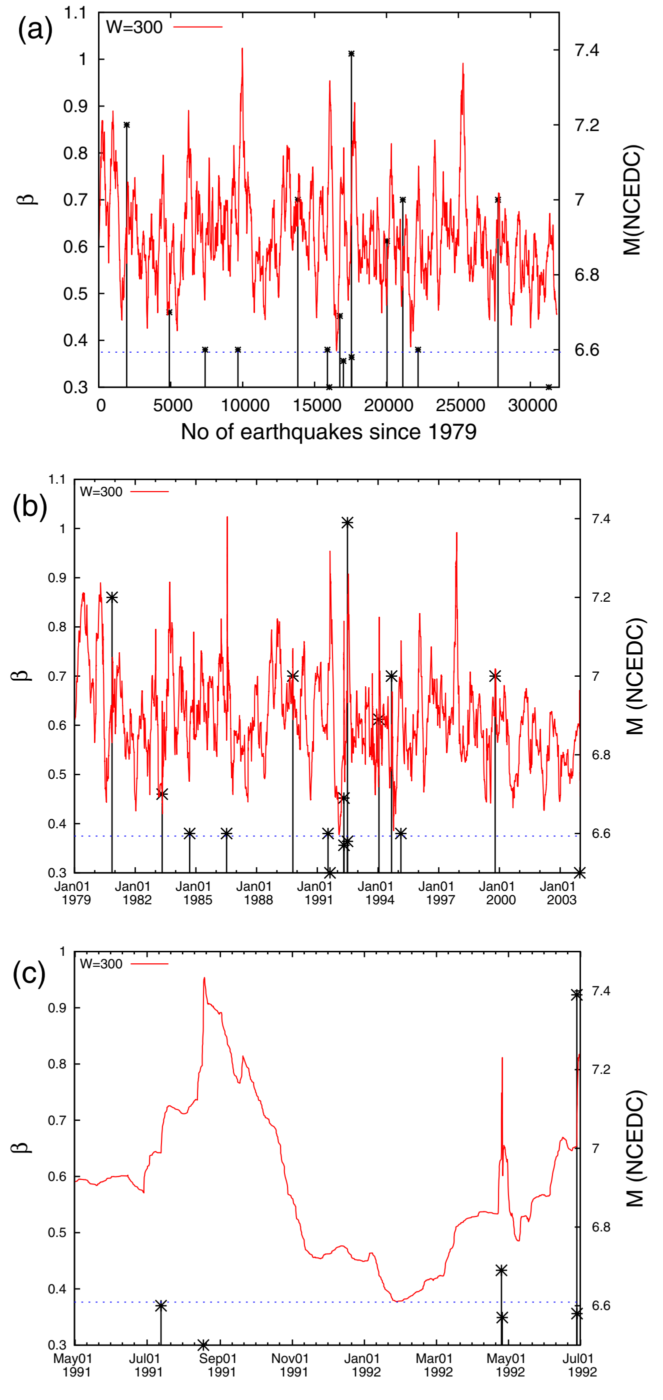

Fig. 1: (Color online) (a) The variability of κ_1 *vs.* the number of events (earthquakes) when a natural time window of length $W = 300$ events is sliding through the NCEDC catalog for the seismicity ($M \geqslant 2.5$) in California during the 25 year period January 1, 1979 to December 31, 2003. The earthquakes that occurred are shown in black (with magnitudes labelled $M(NCEDC)$ in the right scale). (b) The same as in (a) but here the variability of κ_1 is plotted *vs.* the conventional time (UT). (c) An excerpt of (b) showing the variability of κ_1 *vs.* the conventional time during the almost 14 month period from 00:00 UT May 1, 1991 until the occurrence of the Landers earthquake on June 28, 1992. The horizontal dotted (blue) lines were drawn as a guide to the eye indicating the minimum β value.

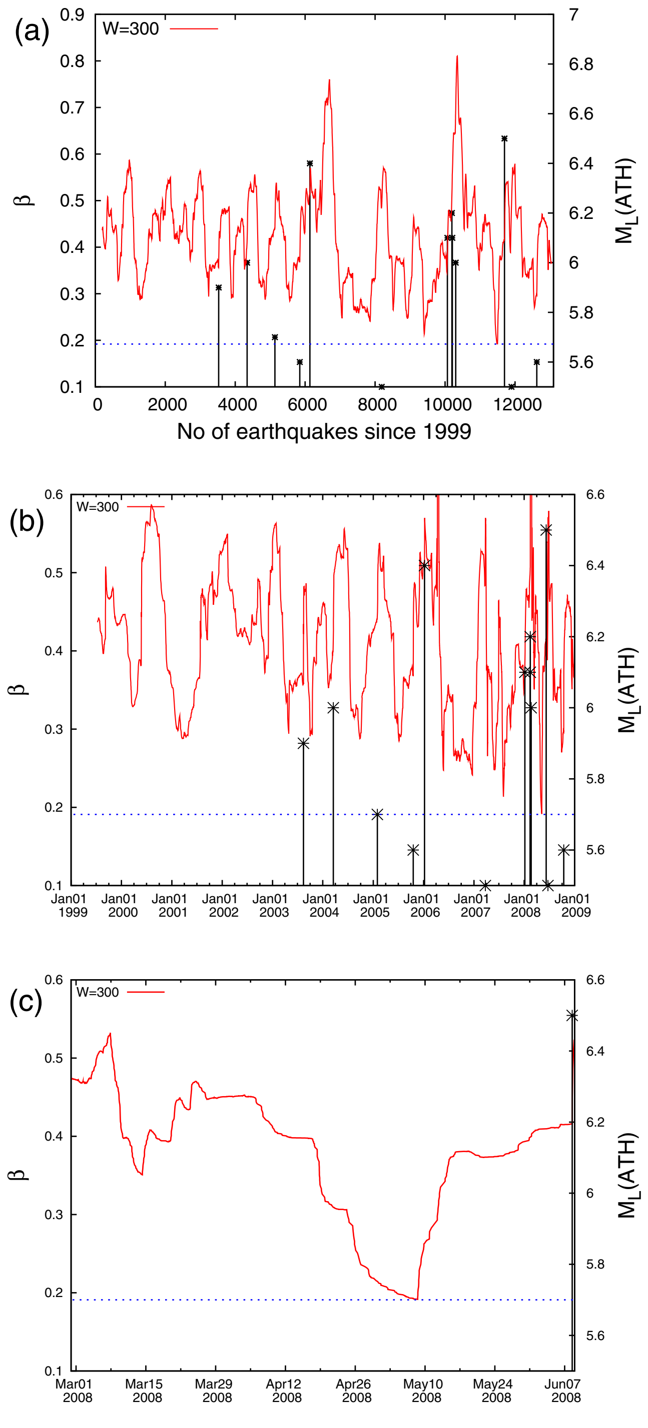

Fig. 2: (Color online) (a) The variability of κ_1 *vs.* the number of events (earthquakes) when a natural time window of length $W = 300$ events is sliding through the GI-NOA catalog for the seismicity ($M_L \geqslant 3.2$) in the area $\mathrm{N}_{34.0}^{39.5}\mathrm{E}_{19.5}^{25.0}$ in Greece during the ten year period January 1, 1999 to December 31, 2008. The earthquakes that occurred are shown in black ($M_L(ATH)$ in the right scale). (b) The same as in (a) but here the variability of κ_1 is plotted *vs.* the conventional time (UT). (c) An excerpt of (b) showing the variability of κ_1 *vs.* the conventional time during an almost three month period from 00:00 UT March 1, 2008 until the $M_L(ATH) = 6.5$ earthquake on June 8, 2008. The horizontal dotted (blue) lines were drawn as a guide to the eye indicating the minimum β value.

April 2008 a decrease of the κ_1 variability becomes evident exhibiting a minimum equal to 0.19 on May 8, 2008, almost one month before the $M_L(ATH) = 6.5$ earthquake. Such a minimum has *not* been observed again since the beginning (January 1, 1999) of the period studied.

An inspection of figs. 1(a), (b) shows that the appearance of the lowest value of the κ_1 variability almost five months before the occurrence of the strongest earthquake during a 25 year period in California is clear, but may be thought marginal. The same holds more or less, for the lowest value of κ_1 almost one month before the strongest earthquake in Greece during the 10 year period in figs. 2(a), (b). This, which is likely due to the fact that the magnitude of the strongest earthquake does not exceed significantly the magnitudes of other earthquakes that occurred during each of the corresponding periods studied in figs. 1(a), (b) and 2(a), (b) for California and Greece respectively, is strengthened by the following fact: Upon repeating the same analysis by considering a natural time window comprising $W(= 200\text{–}500)$ consecutive seismic events sliding through the available seismic catalog of Japan until the 2011 M9.0 Tohoku earthquake, we find that the variability of κ_1 exhibits its lowest value (and hence a *very* clear global minimum) a few to several weeks before the mainshock occurrence, which has never appeared before. In particular, for $W = 200$ and 300 the global minimum appears during the first week of January 2011 and for $W = 500$ on February 5, 2011, while the mainshock occurred on March 11, 2011. Details on this *unprecedented* feature of the order parameter fluctuations, of seismicity in Japan, the identification of which is achieved without making use of any adjustable parameter, will appear elsewhere [44] along with the relevant data analysis and challenging results after the occurrence of Tohoku earthquake. We emphasize that the phenomenon under discussion does not exist for natural time windows, *e.g.*, $W \gtrsim 1000$, appreciably longer than those corresponding to the SES activities lead time.

Conclusions. – Motivated from the concept that SES are emitted when the future focal region enters the critical stage, we employed a fixed natural time window of length comparable to the lead time of the SES activities, sliding through the California seismic catalog over a twenty five year period (1979–2003) and the Greek seismic catalog over a ten year period (1999–2008). In both cases the κ_1 fluctuations of the order parameter of seismicity exhibited a global minimum value well before (*i.e.*, somewhat less than five months and one month, respectively) the strongest earthquake. This provides one pillar of the behavior of the κ_1 fluctuations before the strongest earthquake. The other pillar is the one originating from the bimodal feature of $P(\kappa_1)$ *vs.* κ_1 discussed in ref. [22], *i.e.*, that upon considering various natural time window lengths ending at a given mainshock, the fluctuations of κ_1 considerably increase upon approaching the mainshock.

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