NATURAL TIME ANALYSIS OF COMPLEX TIME SERIES

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NATURAL TIME (*φυσικός χρόνος*)

It was suggested by P. Varotsos, N. Sarlis and E. Skordas, *Practica of Athens Academy* **76**, 294 (2001). It extracts signal information as much as possible *Phys. Rev. Lett*. **94**, 170601 (2005) . For a recent review see P. Varotsos, N. Sarlis and E. Skordas "Natural Time Analysis: The New View of Time" Springer-Verlag (2011).

Ion current fluctuations in membrane channels

exhibit properties described by the "uniform" distribution which is completely different from those of SES (critical dynamics)

Phys.Rev.E **66**, 011902 (2002)

Analysis of electrocardiograms in natural time:

The **sudden cardiac death** individuals are distinguished from the truly healthy ones as well as from patients.

Phys. Rev. E **70**, 011106 (2004);*Phys. Rev. E* **71**, 011110 (2005);*Appl. Phys. Lett.* **91**, 064106(2007); *EPL* **87**, 18003 (2009)

The **entropy** S changes to S- **under time reversal**.

*Phys.Rev.E***71**, 032102 (2005) and its change can be used for predicting the avalanches in the OFC Tectonophysics **513**, 49 (2011)

Discrimination of SES activities (strongest memory) from **noise** emitted from nearby artificial sources

*Phys.Rev.E***67**, 021109 (2003); *CHAOS* **19**, 023114(2009); **20** 033111 (2010); *Tectonophysics* **503**, 189-194 (2011).

Earthquakes:

- Universal curve
- Order parameter
- which exhibits characteristic fluctuations before mainshocks
- Identify correlations between earthquake magnitudes
- Studying the seismicity after an SES activity, we can determine **the time-window of the impending mainshock** with good accuracy of a few hours to a few days.
- Predict the magnitude of aftershocks

Similar looking signals that are emitted from systems **with different dynamics** can be distinguished.

Modern techniques of statistical physics, e.g., Hurst Analysis, Wavelet transform, Detrended Fluctuation Analysis (DFA) etc. should be better made in natural time.

Phys. Rev. E **68**, 031106 (2003)

- High **Tc-superconductors**

(Small changes in the magnetic field can result in large rearrangements of fluxing the sample, known as flux avalanches)

- **Rice piles**

(**S**elf **O**rganized **C**riticality)

Phys.Rev.B **73**, 054504 (2006); *EPL* **96**, 28006 (2011)

- **Critical Systems** in general

Proc. Nat. Acad. Sc. USA **108**, 11361-11364 (2011)

Applications of Natural Time to Earthquakes:

- Universal curve *Phys. Rev. E* **72** , 041103 (2005);**82**, 021110 (2010), *EPL* **100** 39002 (2012)
- Order parameter *Phys. Rev. E* **72** , 041103 (2005)
- which exhibits characteristic fluctuations before mainshocks

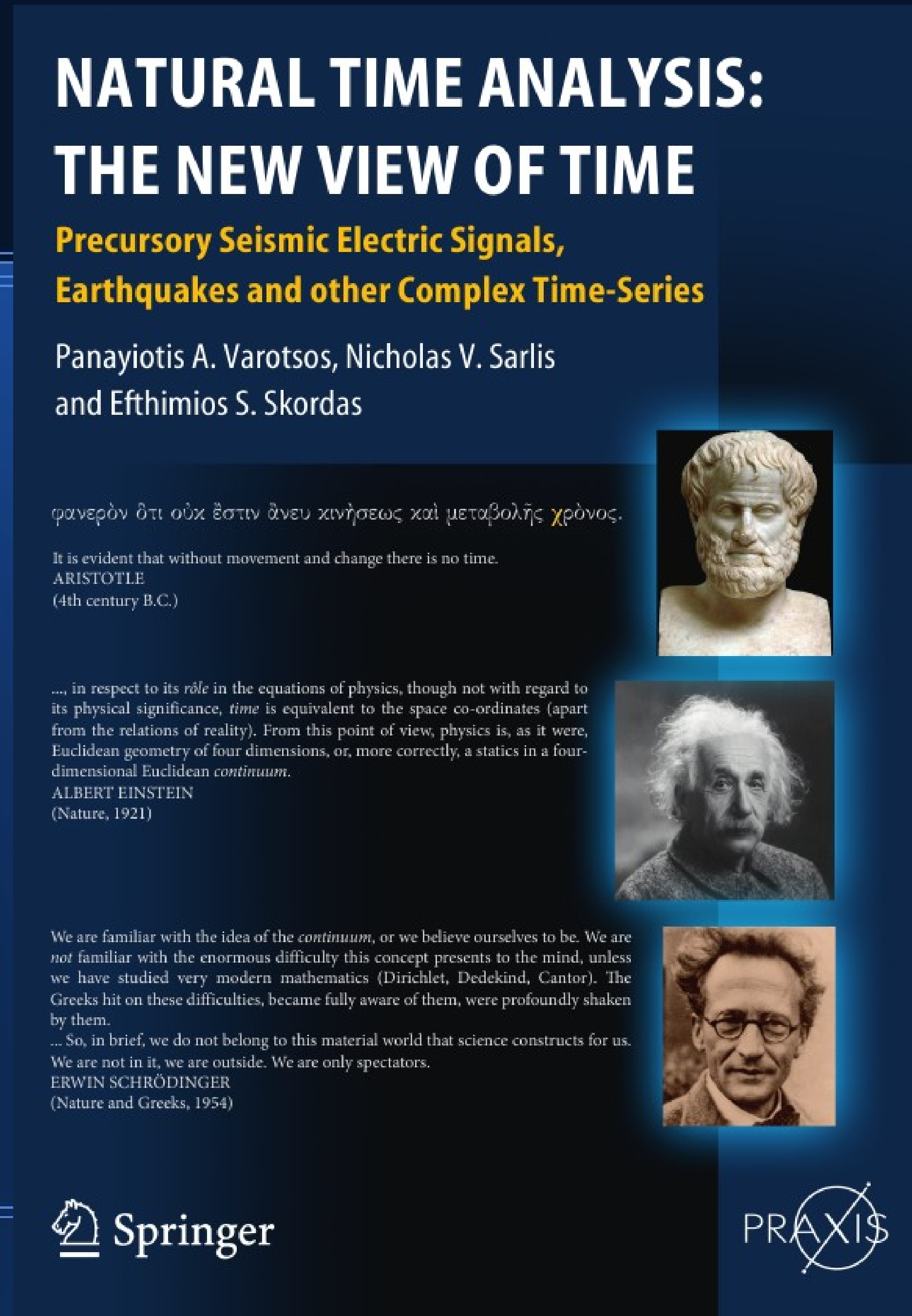
EPL **91**, 59001(2010); **96** 59002 (2011); **99** 59001 (2012),
Nat. Hazards Earth Syst. Sci. **12**, 3473–3481(2012),
Tectonophysics **589**, 116-125(2013)

- Identify correlations between earthquake magnitudes *Phys. Rev. E* **74**, 051118 (2006); **80**, 022102 (2009); **84**, 022101 (2011), *CHAOS* **22**, 023123 (2012)
- Studying the seismicity after an SES activity, we can determine **the time-window of the impending mainshock** with good accuracy of a few hours to a few days.

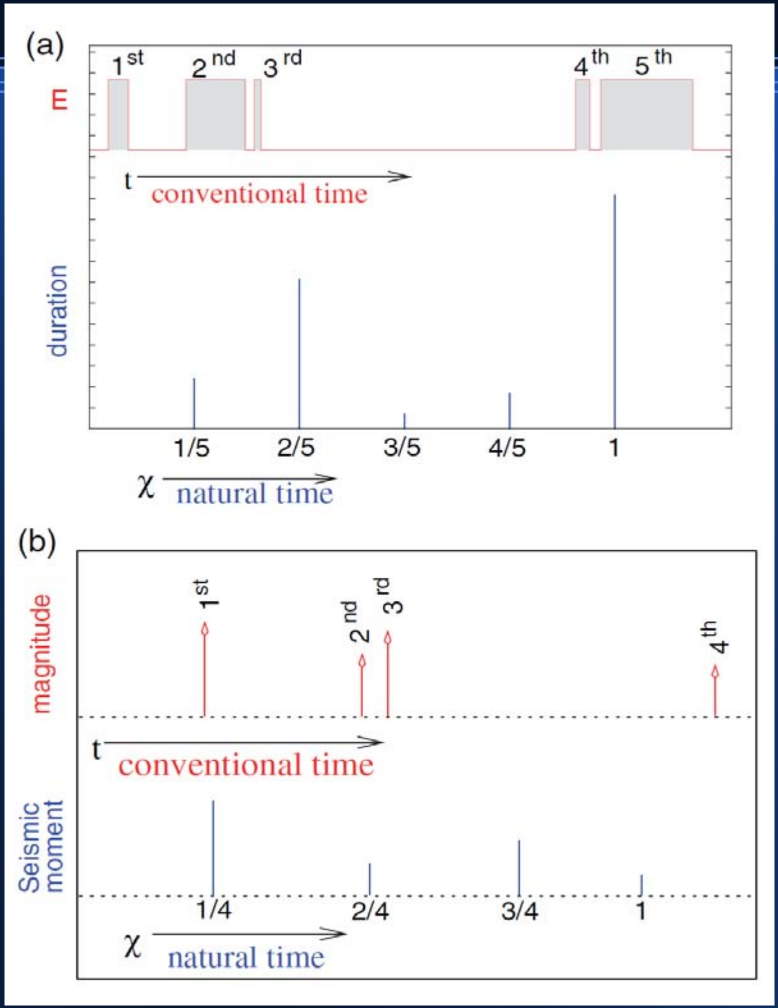
Phys. Rev. E **72**, 041103 (2005); **73**, 031114 (2006); *E* 74, 021123 (2006), *J. Appl. Phys.* **103**, 014906 (2008), *Proc. Jpn Acad. Ser. B* **84**, 331-343 (2008), *J. Geophys. Res.* **114** B02310 (2009); *EPL* **92**, 29002 (2010)

- Predict the magnitude of aftershocks: *Phys. Rev. E* . **85,** 051136 (2012)

The book entitled "NATURAL TIME ANALYSIS: THE NEW VIEW OF TIME, Seismic Electric Signals, Earthquakes and other complex time series" by P. Varotsos, N. Sarlis and E. Skordas appeared in 2011 by **Springer.**



Introduction to Natural Time Analysis (NTA)

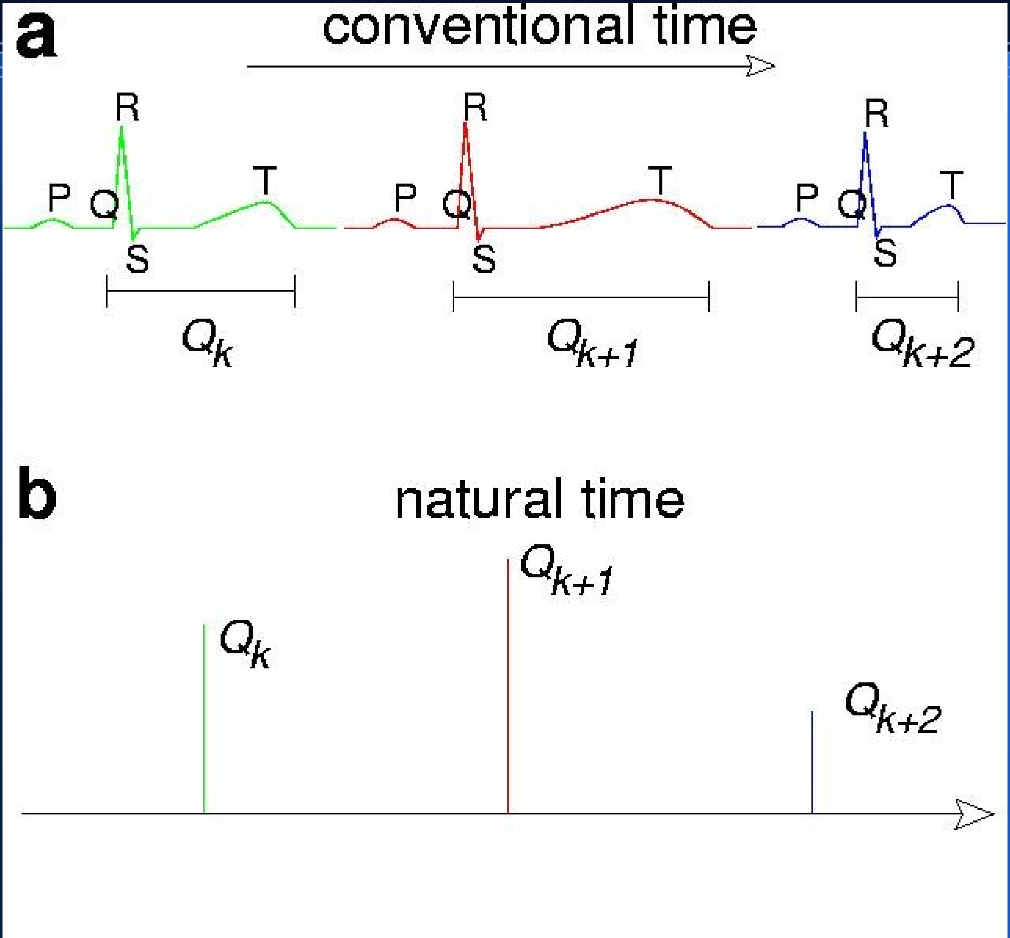


P. Varotsos, N. Sarlis, and E. Skordas, *Practica of Athens Academy* **76**, 294 (2001)

- Let us assume a time series comprising N events. In NTA, the first event is \`placed' on the horizontal axis at χ_1=1/N, the second at χ_2=2/N etc. In general, the event that occurred k-th in order is placed at χ_k=k/N.
  - *We call χ_k=k/N natural time.*
  - *For each event k, we consider a quantity Q_k which is, in general, proportional to the released energy E_k.*

In NTA, we study the evolution of the pair (χ_k,Q_k) .

NTA in electrocardiograms



Schematic diagram of a three heartbeat excerpt of an ECG in the usual (conventional) time−domain (a), and the QT−interval time−series of (a) read in the natural time (b). The vertical bars are equally spaced, but the length of each bar denotes the duration of the corresponding QT−interval marked in (a).

In order to study the evolution of the pairs (χ_k, Q_k) in natural time analysis, we define the normalized energy release:

$$p_k = Q_k / \sum_{n=1}^{N} Q_n$$

- Since p_k are positive and sum up to unity they can be considered as probabilities. Thus,

$$\Phi(\omega) = \langle \exp(i\omega\chi) \rangle = \sum_{n=1}^{N} p_n \exp(i\omega\chi_n)$$

or $\Pi(\omega) = |\Phi(\omega)|^2$

may be considered as characteristic functions for the distribution of p_k in the sense of Probability Theory.

P. Varotsos, N. Sarlis, and E. Skordas, *Practica of Athens Academy* **76**, 294 (2001)

The variance κ_1 of natural time

Since characteristic functions provide information on the distribution when $\omega \to 0$, we study $\Pi(\omega)$ in this limit:

As $\omega \to 0$, $\Pi(\omega) \approx 1 - \kappa_1 \omega^2$

where

$$\kappa_1 = \langle \chi^2 \rangle - \langle \chi \rangle^2 = \sum (\chi_k)^2 p_k - \left(\sum \chi_k p_k\right)^2$$

is the variance of natural time.

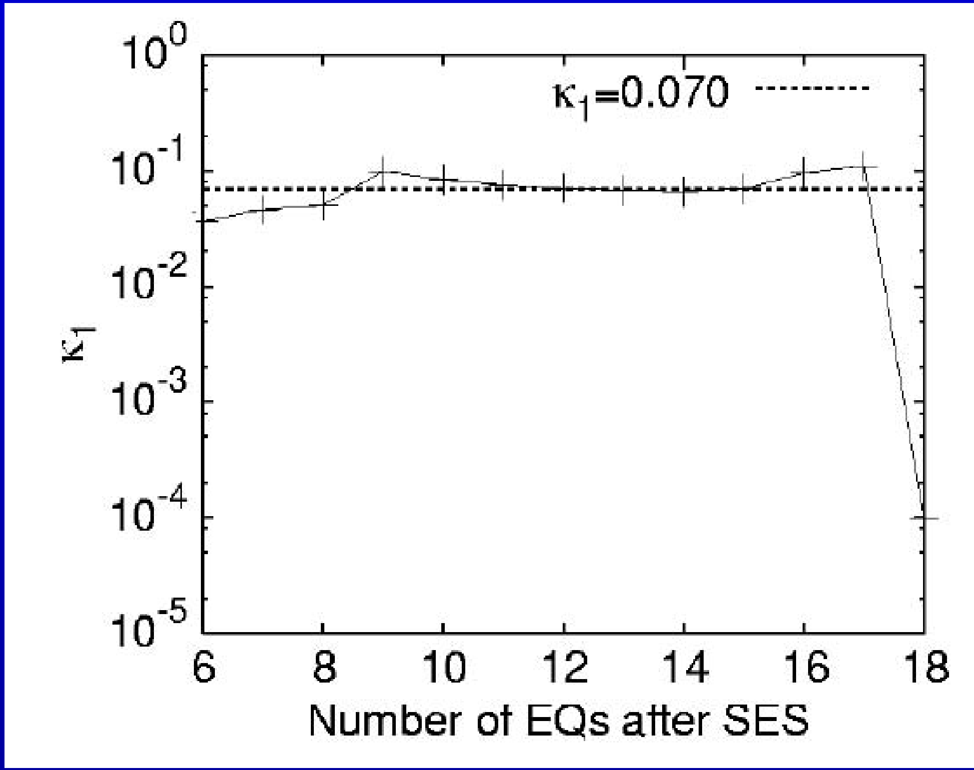
P. Varotsos, N. Sarlis, and E. Skordas, *Practica of Athens Academy* **76**, 294 (2001)

Important properties of κ_1

*The quantity κ_1, or equivalently the quantity $\Pi(\omega)=|\Phi(\omega)|^2$ for $\omega\rightarrow 0$, has been proposed as an *order parameter (OP)* for seismicity. [P. Varotsos et al. *Phys. Rev. E* **72**, 041103 (2005)]

*For systems at criticality the following condition holds $\kappa_1=0.070$
[P. Varotsos et al. *Proc. Nat. Acad. Sc. USA* **108,** 11361-11364 (2011)]

Why κ_1 behaves like an OP for EQs?



The value of κ_1 after the Seismic Electric Signal on April 18, 1995 until the 6.6 Kozani-Grevana EQ on May 13, 1995 (labelled 18).

- κ_1 is non-zero before the occurence of a strong earthquake (EQ) (like magnetization M is non-zero below the Curie temperature in the unsymmetrical phase)
- κ_1 becomes zero upon the occurrence of a strong EQ (like M is zero above the Curie temperature in the symmetrical phase)

Varotsos P. A., Sarlis N. V., Tanaka H. K. and Skordas E. S., Phys. Rev. E, 72 (2005) 041103.

The values of κ_1 for various dynamical universality classes

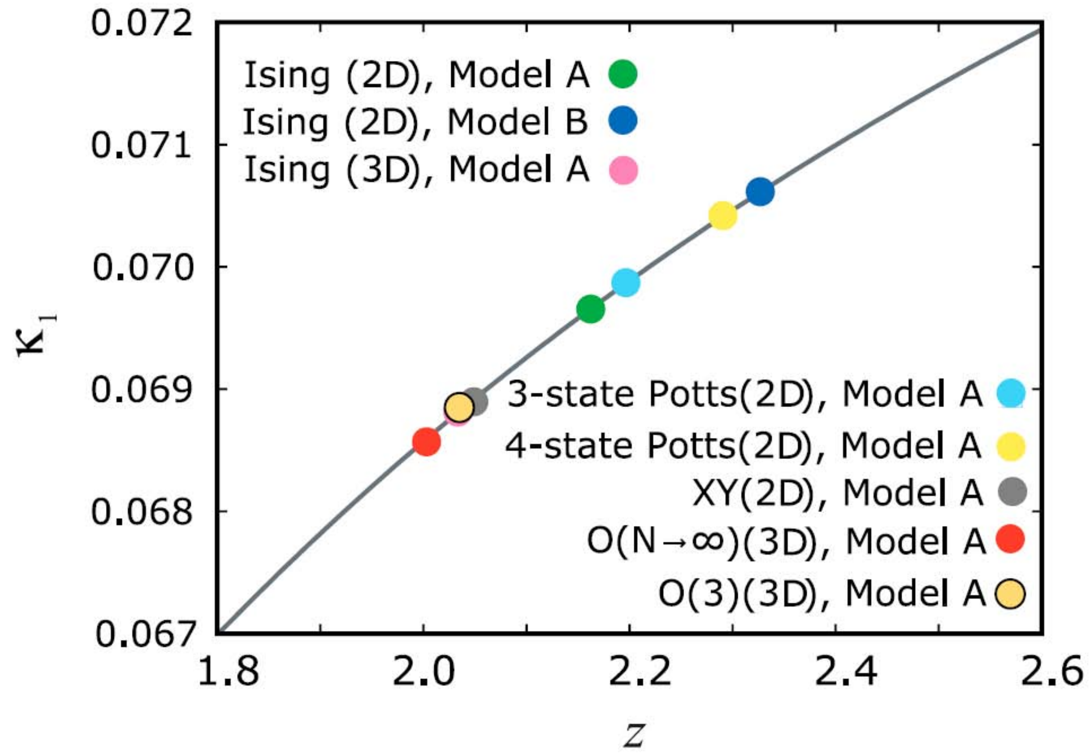
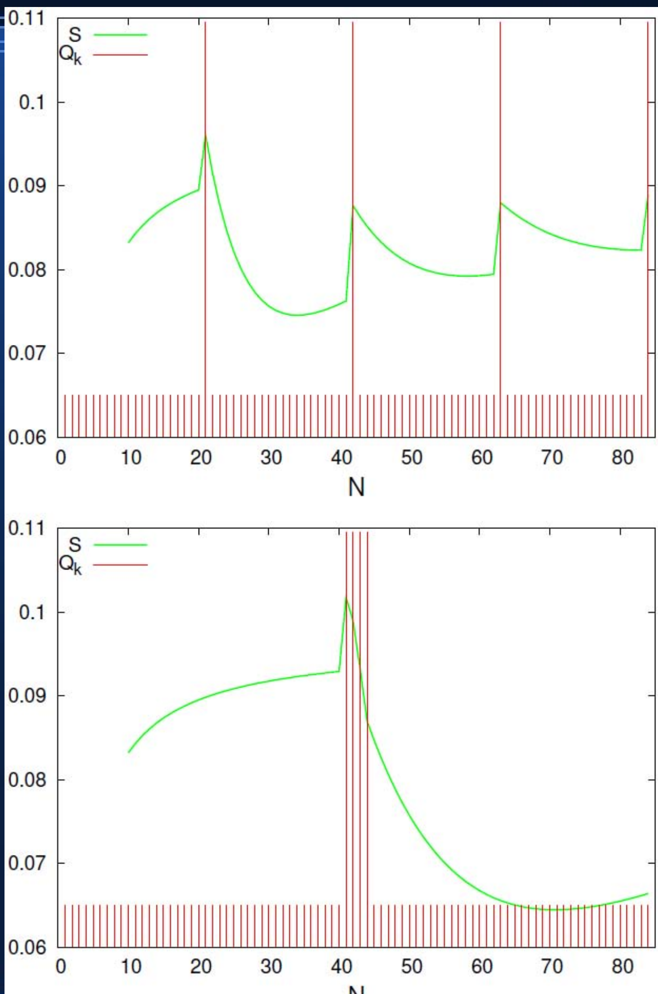


Fig. 1. The values of κ_1 as a function of dynamic critical exponent z. Various dynamical universality classes are depicted according to their dynamic critical exponent values (see tables IV, VII, IX, and XI of ref. 19). Models A and B correspond to nonconserved or conserved order parameter dynamics as defined by Hohenberg and Halperin (33).

P. Varotsos et al. *Proc. Nat. Acad. Sc. USA* **108,** 11361-11364 (2011)

The entropy S in natural time $S=\langle \chi \ln \chi \rangle-\langle \chi \rangle \ln \langle \chi \rangle$



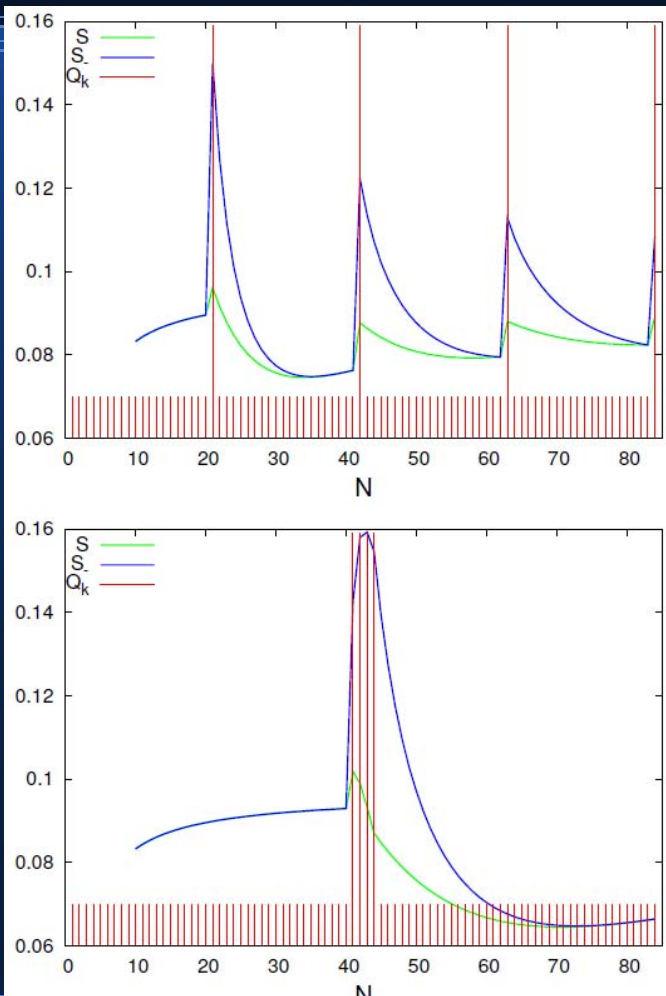
- S is a dynamic entropy and hence differs essentially from the usual (static) Shannon entropy: $-\Sigma p_i \ln p_i$
- When reversing the time arrow, S changes to S_ being a "*causal*" operator

[Varotsos et al., *Phys. Rev. E* 71, 032102 (2005)]

The S value corresponding to the "uniform" distribution is denoted by $S_u=\ln(2)/2-1/4\approx 0.0966$

Varotsos et al., Practica of Athens Academy ***76****, 294* (2001); *Phys. Rev. E* ***68****,* 031106 (2003); *ibid* ***70****,* 011106 (2004)

The entropy S in natural time $S=\langle \chi \ln \chi \rangle - \langle \chi \rangle \ln \langle \chi \rangle$



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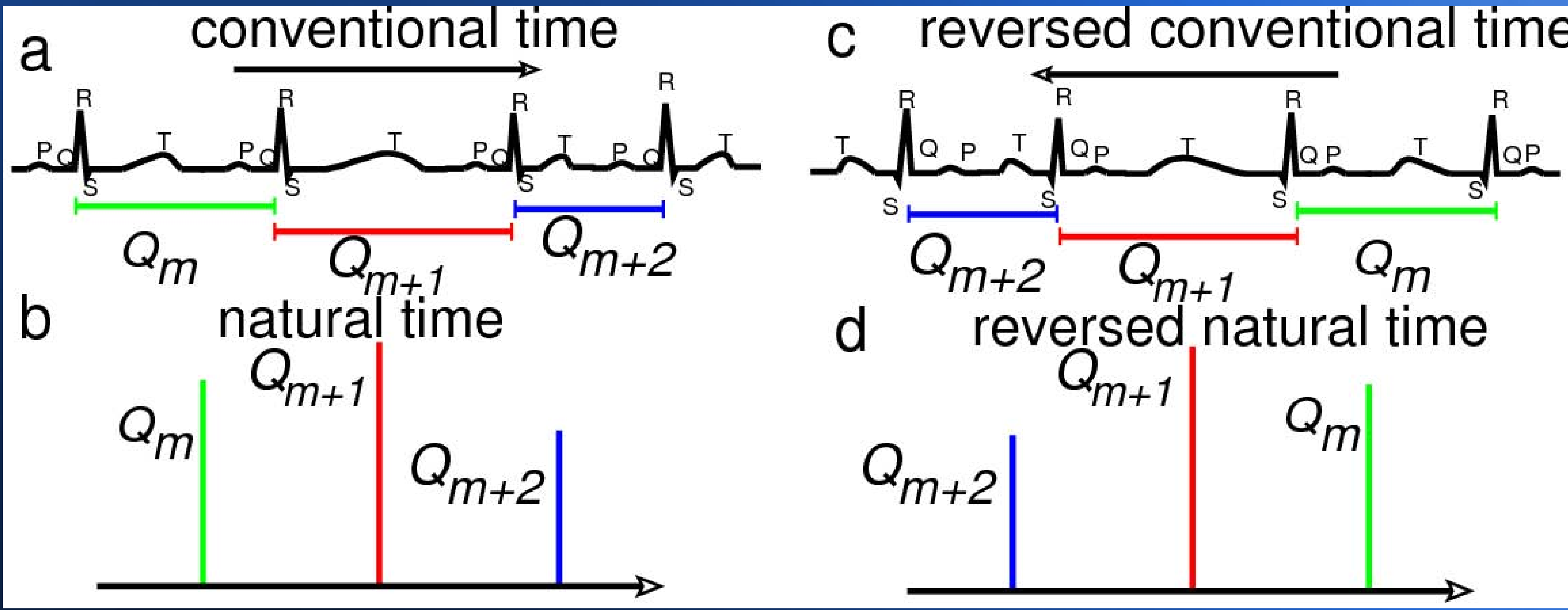
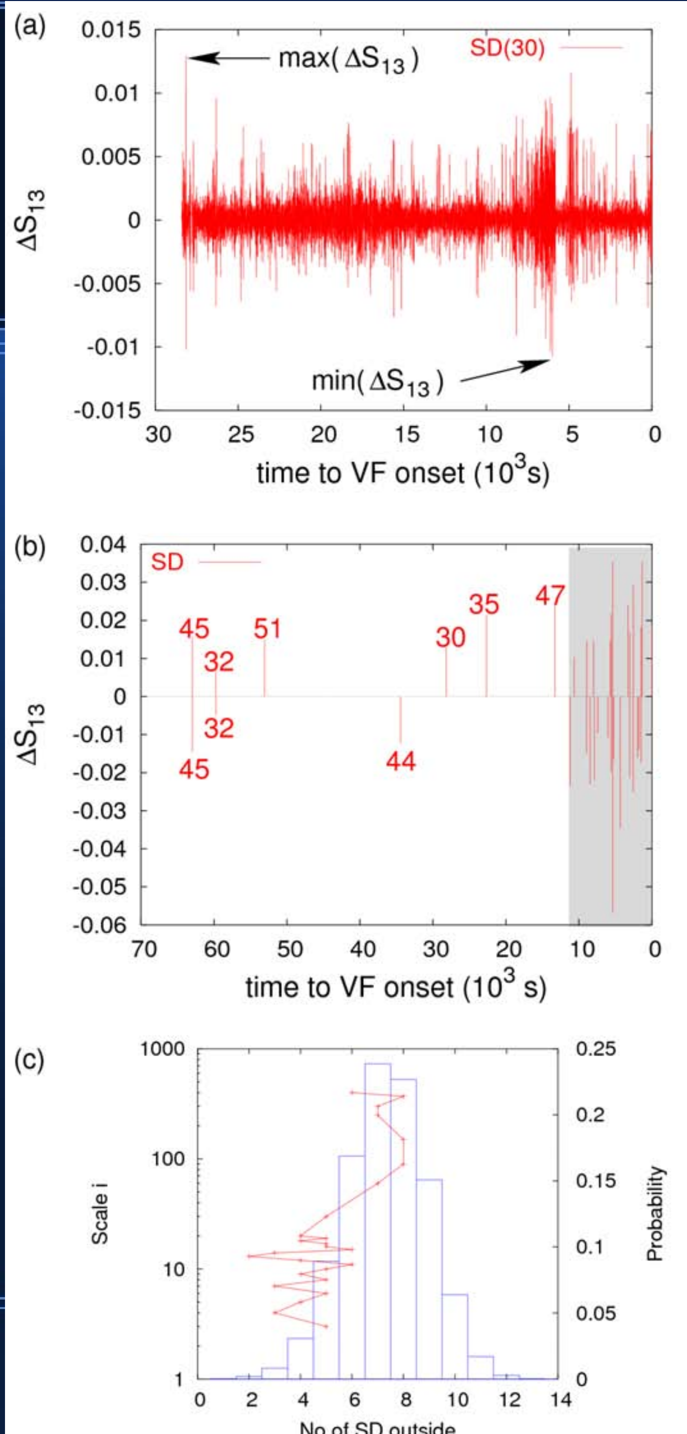
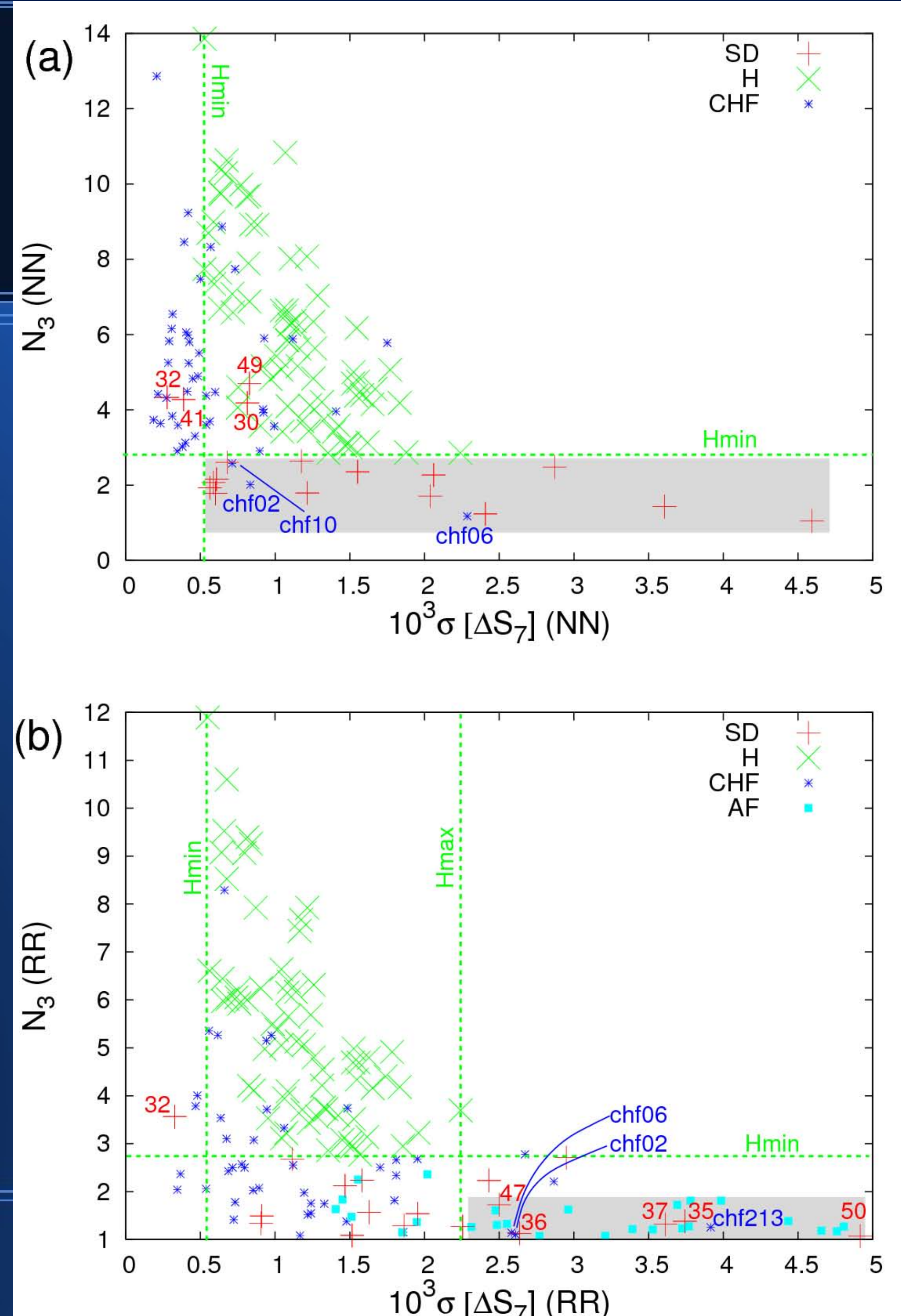
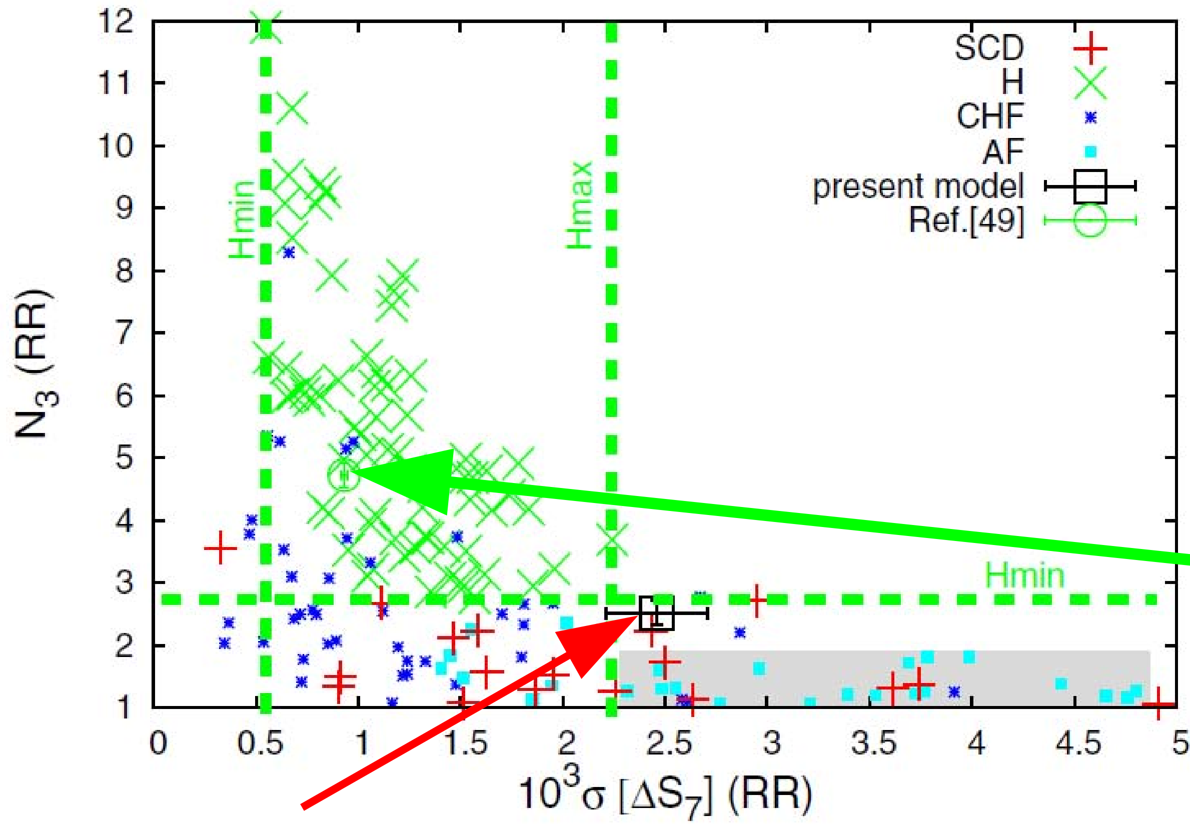
Varotsos et al., Practica of Athens Academy ***76****, 294* (2001); *Phys. Rev. E* **68**, 031106 (2003); *ibid* ***70***, 011106 (2004)

An application of S_ to ECGs



Varotsos et al., Appl. Phys. Lett. ***91, 0641066 (2007)***


(a)
SD(30)
max(ΔS13)
min(ΔS13)
ΔS13
time to VF onset (10^3s)
(b)
SD
45
32
51
30
35
47
44
ΔS13
time to VF onset (10^3 s)
(c)
Scale i
Probability
No of SD outside

(a)
SD
H
CHF
Hmin
49
32
41
30
chf02
chf10
chf06
N3 (NN)
10^3σ [ΔS7] (NN)
(b)
SD
H
CHF
AF
Hmin
Hmax
32
47
36
37
35
50
chf06
chf02
chf213
N3 (RR)
10^3σ [ΔS7] (RR)

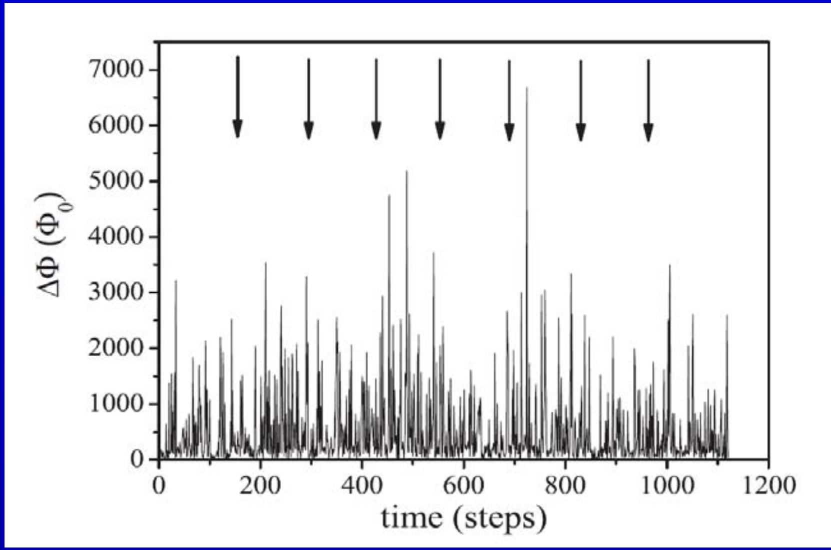


N. Sarlis, E. Skordas and P. Varotsos, *" Heart rate variability in natural time and 1/f "noise"", EPL* **87**, 18003 (2009)

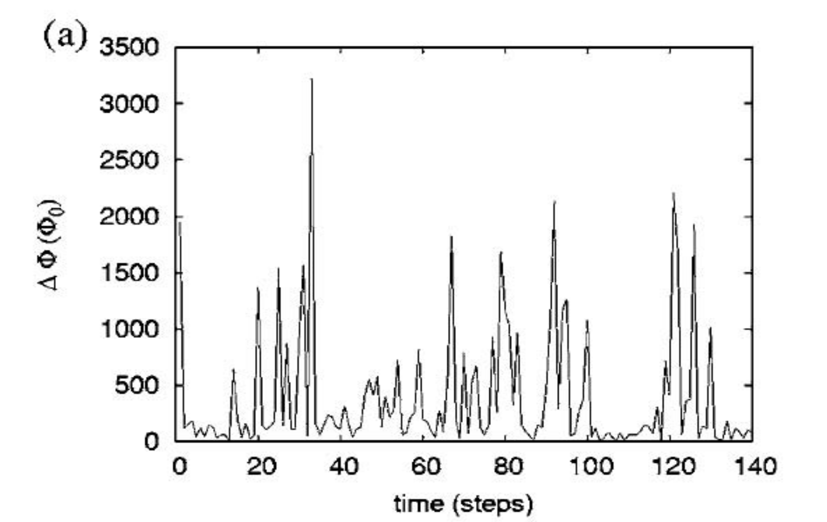
Fig. 5: (Color online) The complexity measure N_3 *vs.* $\sigma[\Delta S_7]$ for the RR time series. The green horizontal line corresponds to the minimum value of N_3, while the two vertical green lines to the minimum and maximum $\sigma[\Delta S_7]$ values, respectively, computed in H. The (black) square and the corresponding error bars depict the values of the complexity measures obtained from the model proposed here. As for the complexity measures obtained from the model suggested in ref. [49] (using the same parameters with those given in fig. 2 of ref. [49]), they correspond to the (green) circle.

[49] Ivanov P.C., Nunes Amaral L. A.,Goldberger A.L. and Stanley H. E. *Europhys. Lett.* **43**, 363 (1998)

Magnetic flux avalanches in $YBa_2Cu_3O_{7-x}$



Aegerter C. M., Welling M. S. and Wijngaarden R. J., Europhys. Lett., 65 (2004) 753.



Sarlis N. V., Varotsos P. A. and Skordas E. S., Phys. Rev. B, 73 (2006) 054504.

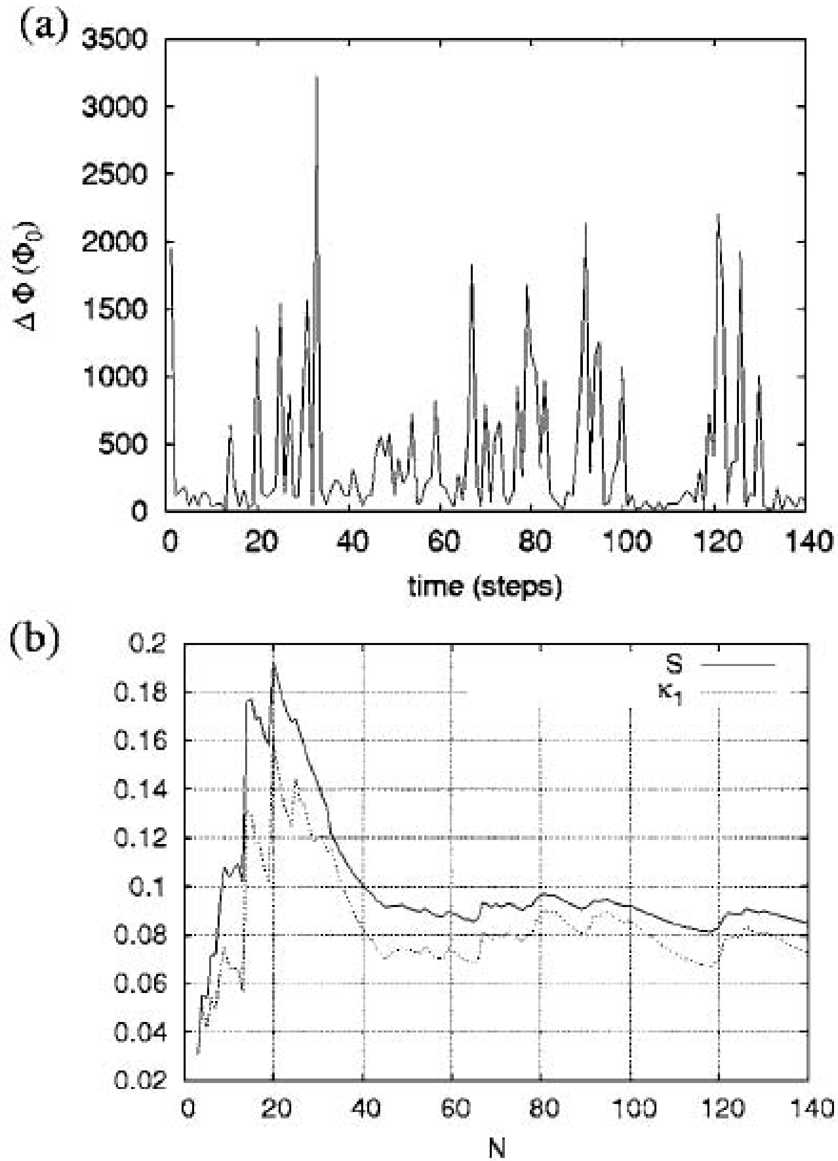


FIG. 1. (a) The time evolution of the magnetic flux
$YBa_2Cu_3O_{7-x}$ inside the sample over the first run of Fig. 2 of R
14. (b) The results of the variance κ_1 (dotted line) and the entrop
(solid line) as they evolve event by event, when the data of (a)
analyzed in the natural time domain.

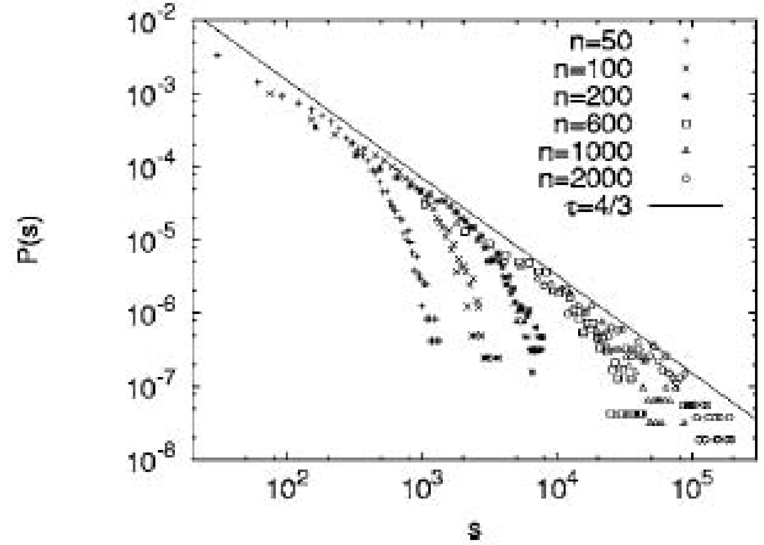


FIG. 2. The PDF $P(s)$ versus the cluster area s of the C clusters of Ref. 16, for H=0.5 for various values of n=50, 100, 200, 600, 1000, and 2000. The line $P(s) \propto s^{-\tau}$ with $\tau=4/3$, as analytically found in Ref. 16 to describe $P(s)$, is also drawn as a guide to the eye.

[16] A. Carbone and H. E. Stanley, Physica A **340**, 544 (2004).

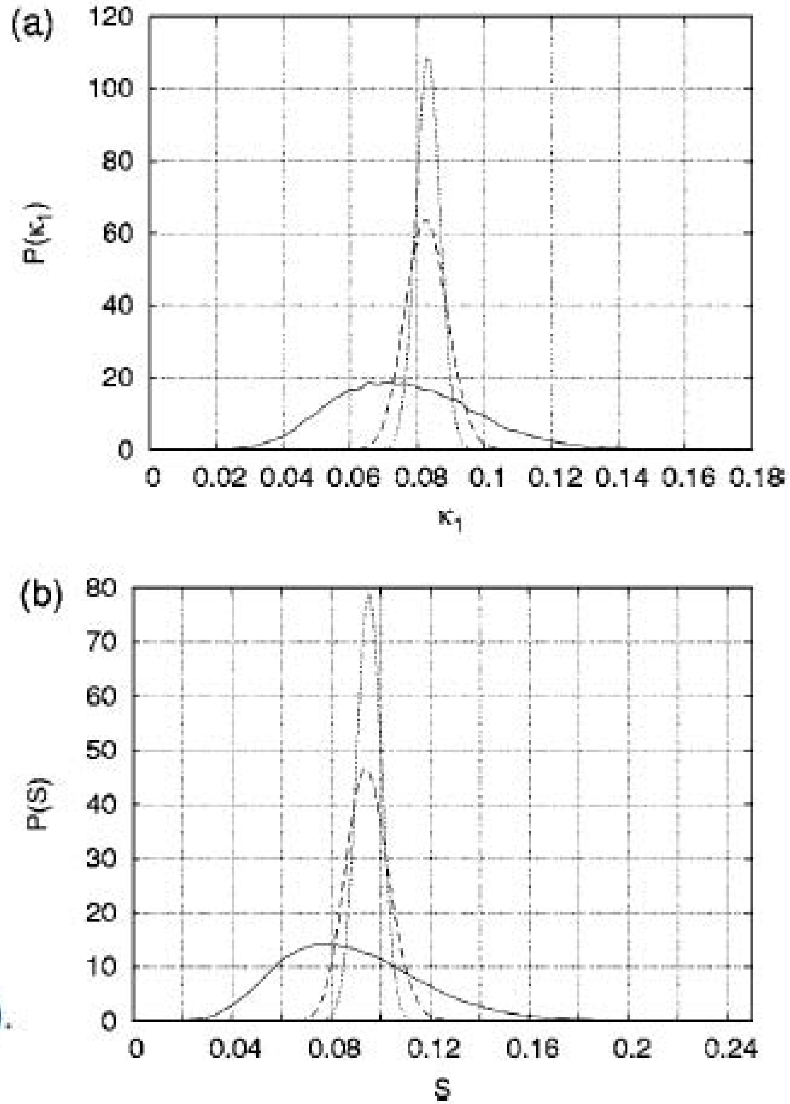
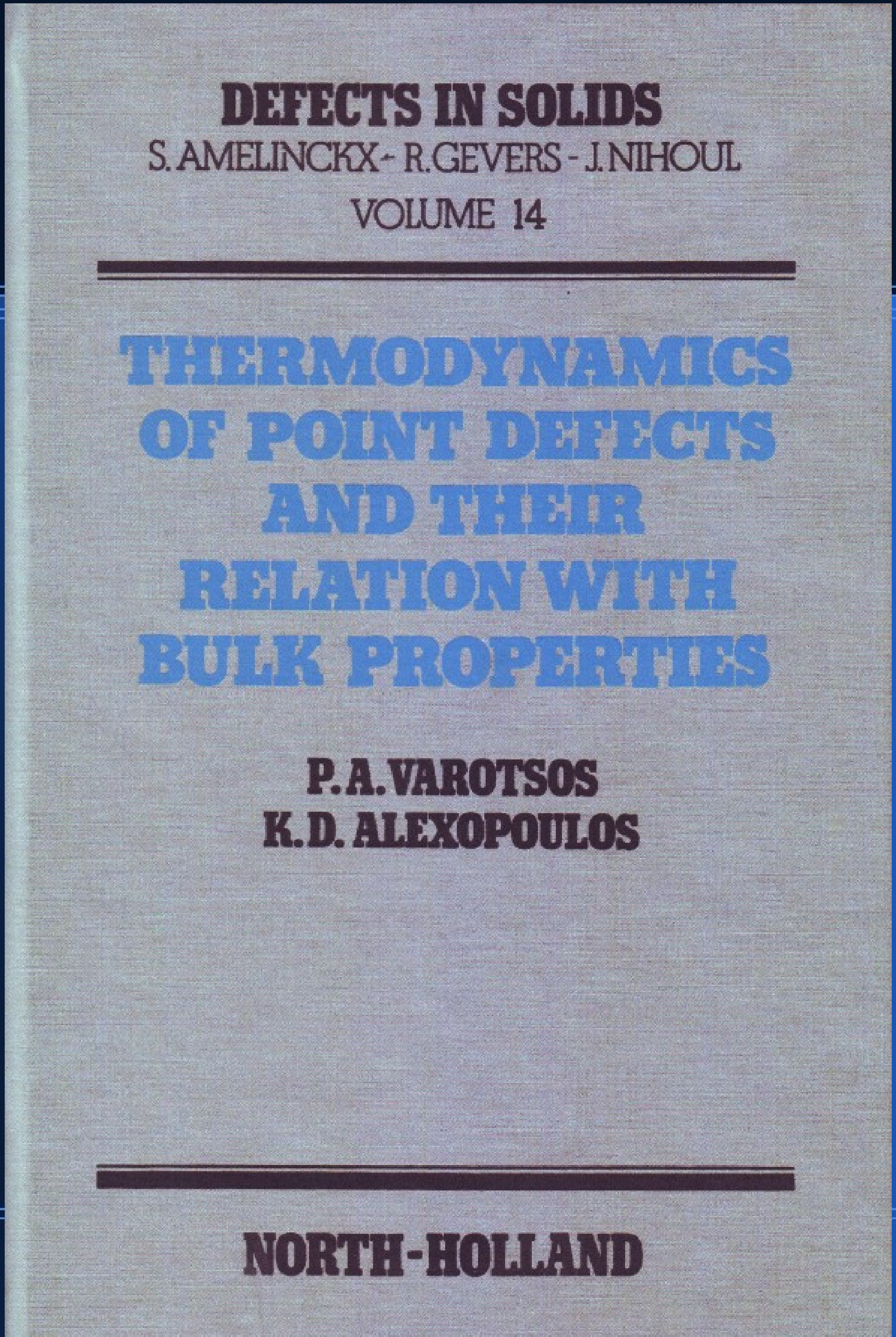


FIG. 3. The PDF's of κ_1 and S obtained from a Monte Carlo simulation for the generalized stochastic model of Ref. 16 for H=0.5, n=200, and N=140. The dotted and dashed PDF's correspond to two different *noncritical* cases (see the text).

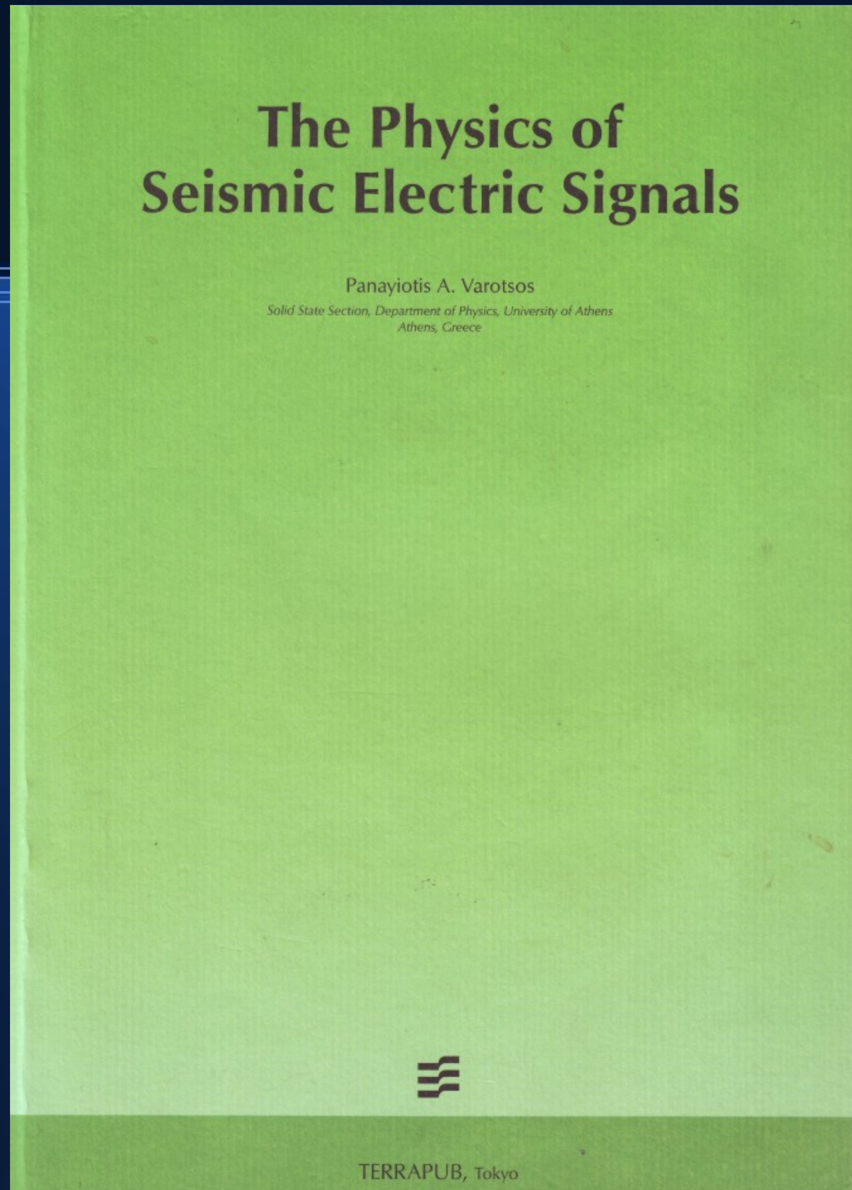
Seismic Electric Signal Activities

Seismic Electric Signals (SES) activities are series of low frequency electric signals that precede earthquakes, reported in the 80’s.

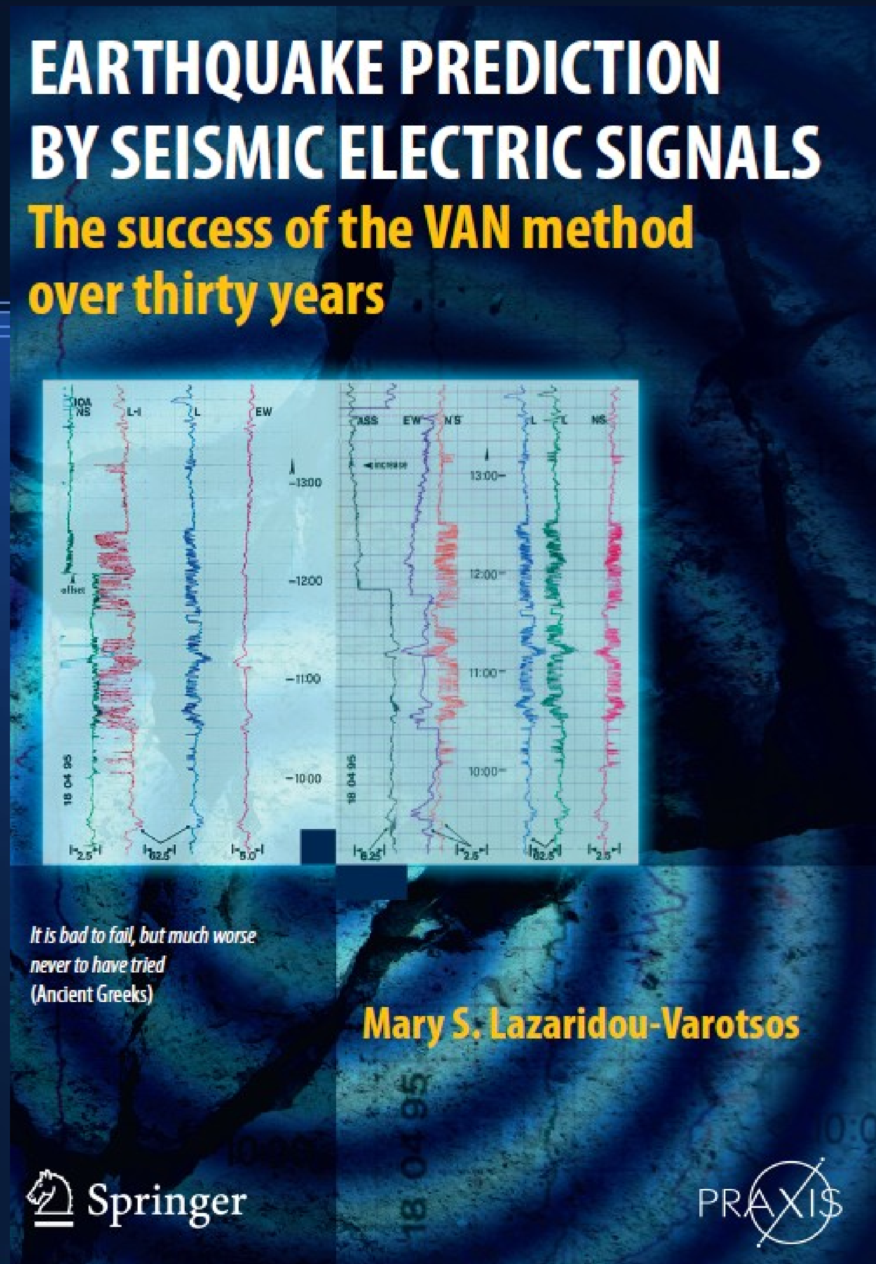
Almost 30 years ago, it has been suggested that SES activities arise from a cooperative orientation of electric dipoles formed due to defects when the stress in the focal area reaches a *critical* value. Cooperativity is a hallmark of *criticality*.


DEFECTS IN SOLIDS
S. AMELINCKX - R. GEVERS - J. NIHOUL
VOLUME 14
THERMODYNAMICS OF POINT DEFECTS AND THEIR RELATION WITH BULK PROPERTIES
P. A. VAROTSOS
K. D. ALEXOPOULOS
NORTH-HOLLAND

1986

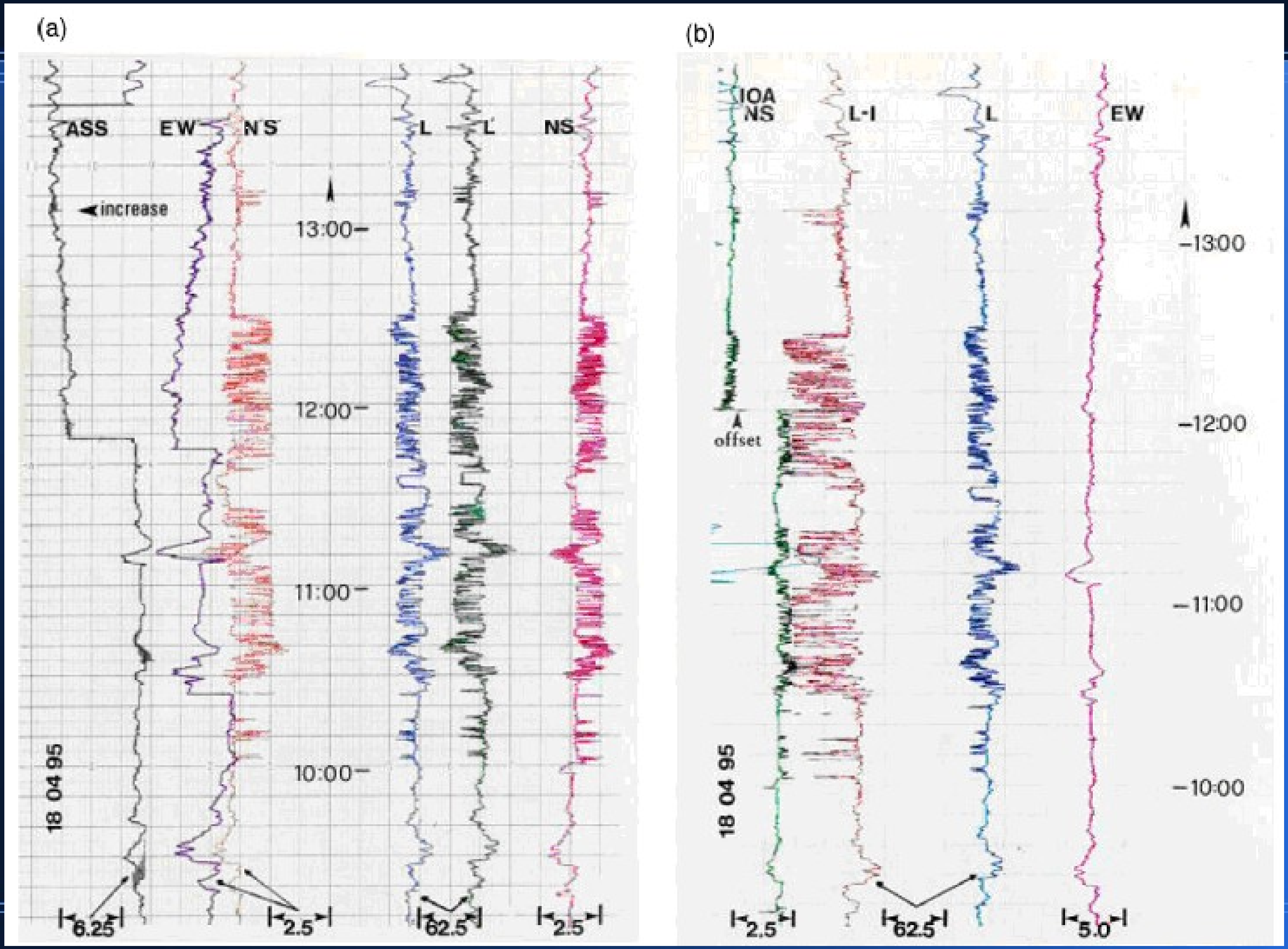


The cover of the book entitled “Physics of Seismic Electric Signals” by P. Varotsos released in 2005 by the Japanese Publishing House *TerraPub* in Tokyo.



The cover of the book entitled “Earthquake prediction by Seismic Electric Signals” by Mary S. Lazaridou-Varotsos released in 2013 by Springer

An SES activity example from 1995



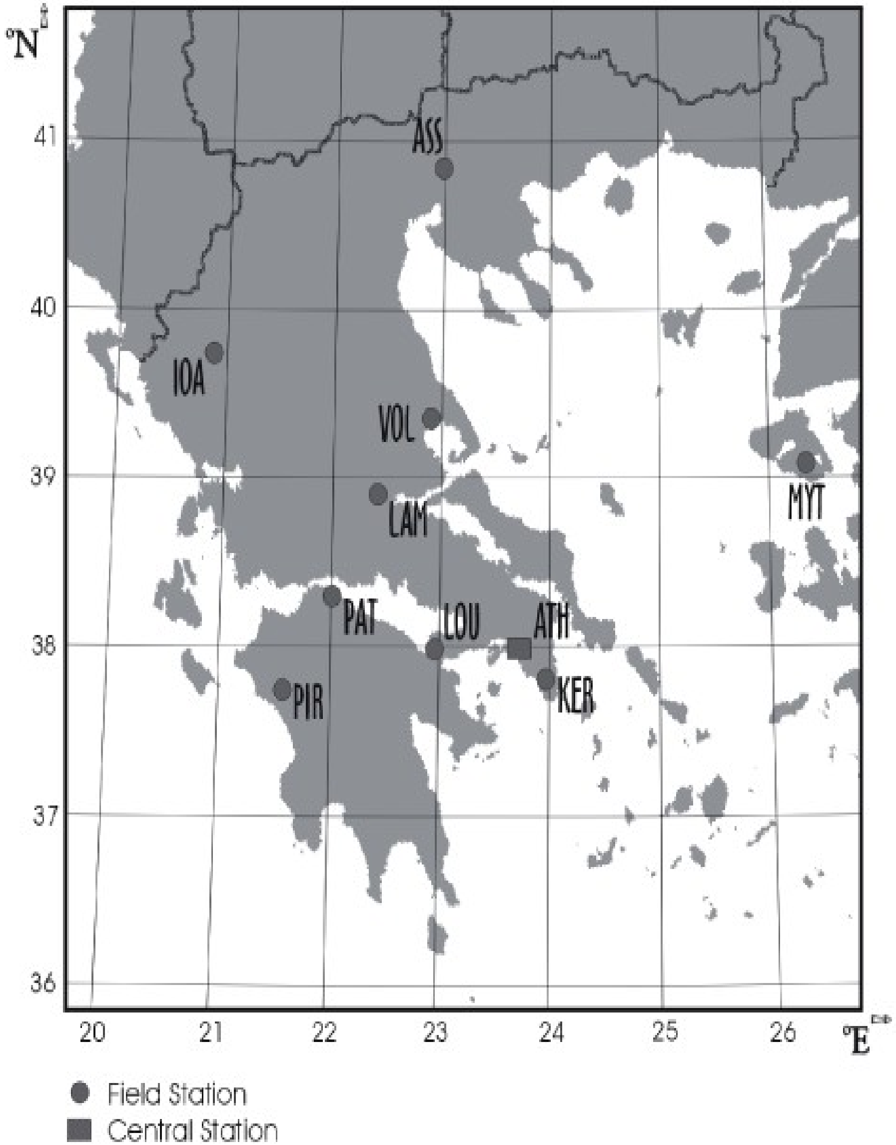
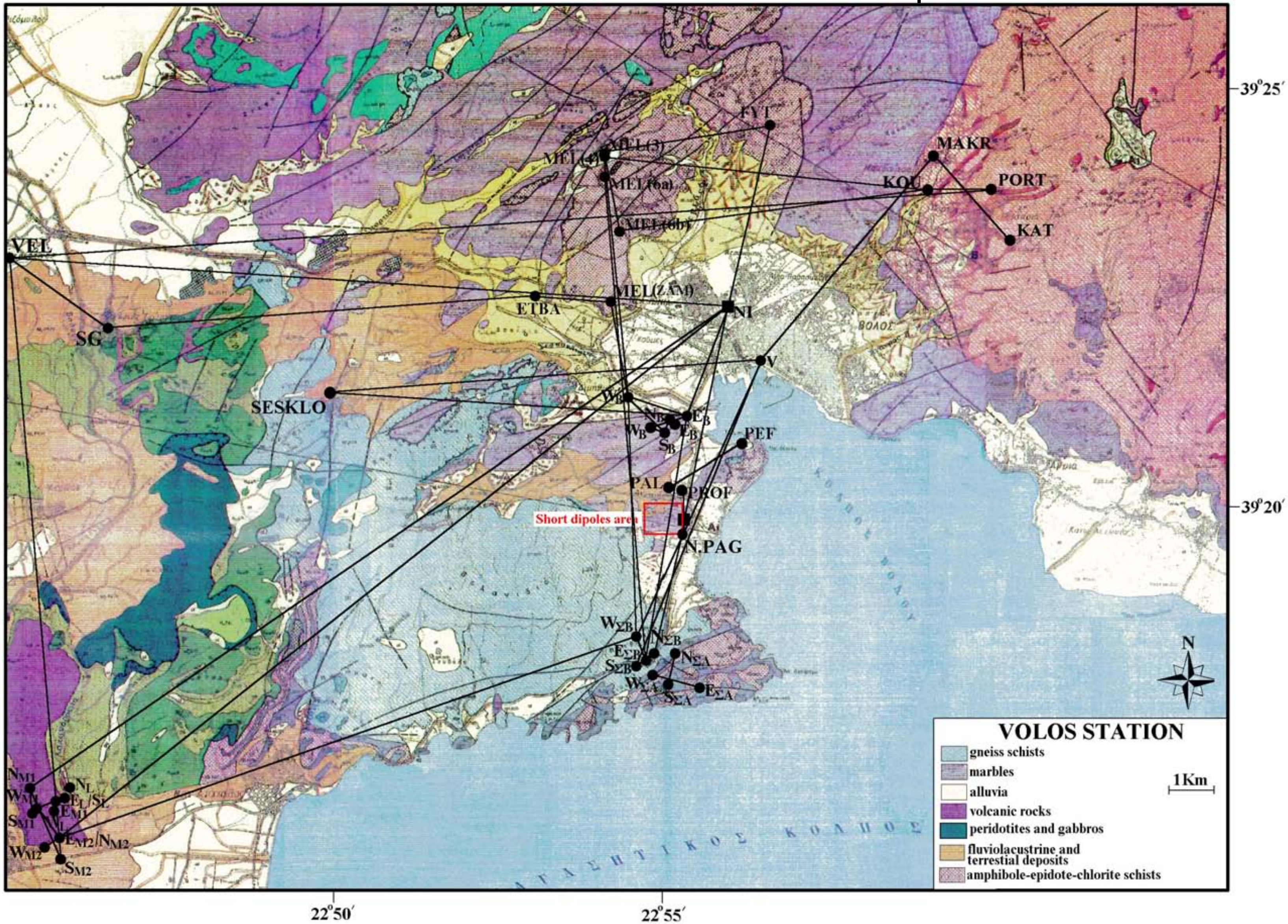


Fig. 1.2 Map showing the sites of the stations of the real-time telemetric network currently operating in Greece.

Dipoles at Volos Station



P. Varotsos, N. Sarlis, and E. Skordas, " A note on the spatial extent of the Volos SES sensitive site", *Acta Geophysica Polonica*, Vol. **49** (2001), 425-435.

1st usefulness of Natural Time

Several Modern Procedures to distinguish true preseismic signals (*critical* dynamics) from “artificial” noise:

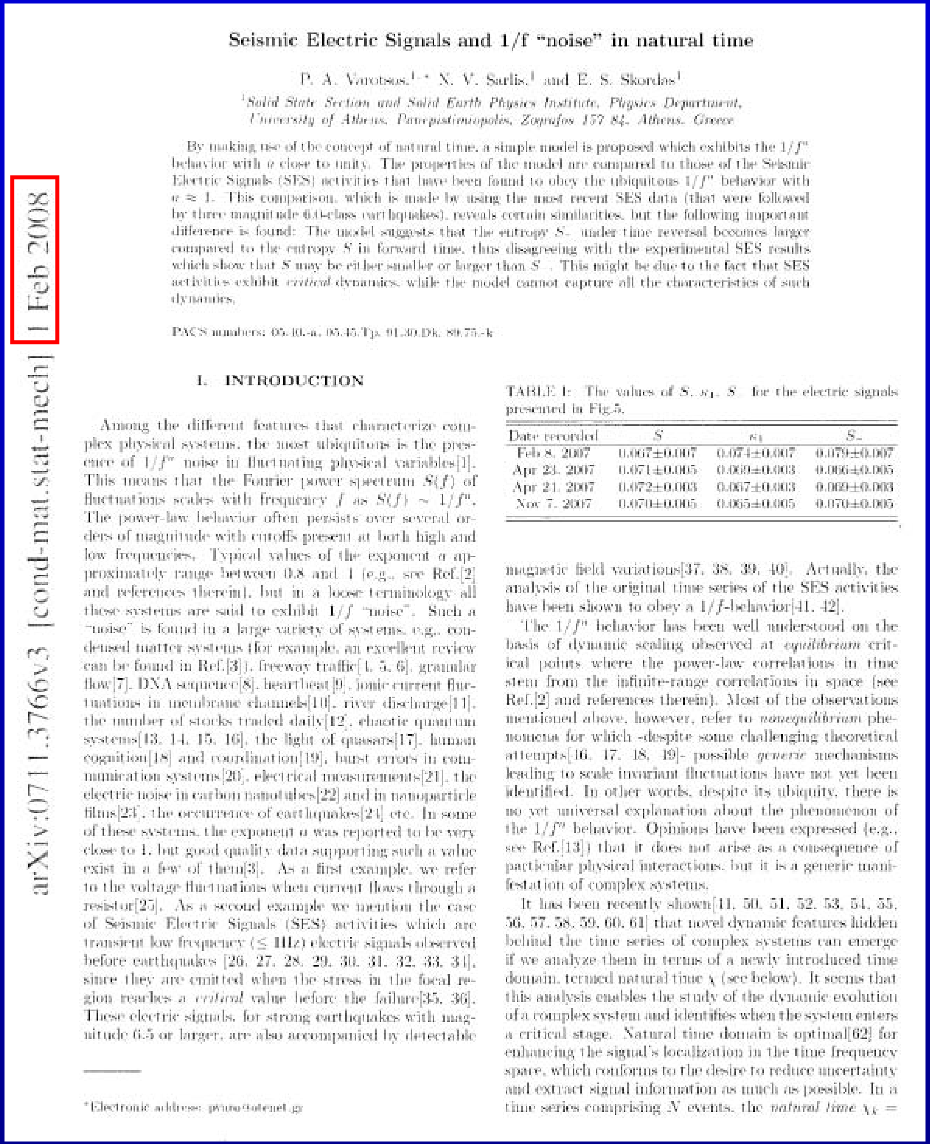
- Normalized power spectrum $\Pi(\omega)$ (*or* $\kappa_1 = \langle \chi^2 \rangle - \langle \chi \rangle^2$)
- Hurst
- Detrended Fluctuation Analysis (DFA)
- Multifractal DFA
- Wavelet Transform
- Entropy

ATTENTION: *All* the above in natural time

Natural time analysis results in the following additional facts:

- First, based on the data of the SES activities and on the natural time analysis of subsequent seismicity, *successful predictions* (concerning the magnitude, epicenter and time-window) have been publicized well in advance, for all five major earthquakes with Mw≥6.4 (related to four mainshocks) in Greece during the last decade [e.g. see Seiya Uyeda and Masashi Kamogawa, EOS, Transactions, American Geophysical Union **89**, 363 (2008); **91**, 163 (2010)].
- Second, the recording of SES activities are shown to be accompanied by characteristic changes of *independent geophysical data*.

Prediction of the largest moment magnitude EQ during the last 30 years in Greece



arXiv:0711.3766v3 [cond-mat.stat-mech] 1 Feb 2008

Seismic Electric Signals and 1/f "noise" in natural time

P. A. Varotsos,[1,*] N. V. Sarlis,[1] and E. S. Skordas[1]

[1] *Solid State Section and Solid Earth Physics Institute, Physics Department, University of Athens, Panepistimiopolis, Zografos 157 84, Athens, Greece*

By making use of the concept of natural time, a simple model is proposed which exhibits the $1/f^a$ behavior with a close to unity. The properties of the model are compared to those of the Seismic Electric Signals (SES) activities that have been found to obey the ubiquitous $1/f^a$ behavior with $a \approx 1$. This comparison, which is made by using the most recent SES data (that were followed by three magnitude 6.0-class earthquakes), reveals certain similarities, but the following important difference is found: The model suggests that the entropy S_- under time reversal becomes larger compared to the entropy S in forward time, thus disagreeing with the experimental SES results which show that S may be either smaller or larger than S_-. This might be due to the fact that SES activities exhibit *critical* dynamics, while the model cannot capture all the characteristics of such dynamics.

PACS numbers: 05.40.-a, 05.45.Tp, 91.30.Dk, 89.75.-k

I. INTRODUCTION

Among the different features that characterize complex physical systems, the most ubiquitous is the presence of $1/f^a$ noise in fluctuating physical variables[1]. This means that the Fourier power spectrum $S(f)$ of fluctuations scales with frequency f as $S(f) \sim 1/f^a$. The power-law behavior often persists over several orders of magnitude with cutoffs present at both high and low frequencies. Typical values of the exponent a approximately range between 0.8 and 1 (e.g., see Ref.[2] and references therein), but in a loose terminology all these systems are said to exhibit $1/f$ "noise". Such a "noise" is found in a large variety of systems, e.g., condensed matter systems (for example, an excellent review can be found in Ref.[3]), freeway traffic[4, 5, 6], granular flow[7], DNA sequence[8], heartbeat[9], ionic current fluctuations in membrane channels[10], river discharge[11], the number of stocks traded daily[12], chaotic quantum systems[13, 14, 15, 16], the light of quasars[17], human cognition[18] and coordination[19], burst errors in communication systems[20], electrical measurements[21], the electric noise in carbon nanotubes[22] and in nanoparticle films[23], the occurrence of earthquakes[24] etc. In some of these systems, the exponent a was reported to be very close to 1, but good quality data supporting such a value exist in a few of them[3]. As a first example, we refer to the voltage fluctuations when current flows through a resistor[25]. As a second example we mention the case of Seismic Electric Signals (SES) activities which are transient low frequency ($\leq$ 1Hz) electric signals observed before earthquakes [26, 27, 28, 29, 30, 31, 32, 33, 34], since they are emitted when the stress in the focal region reaches a *critical* value before the failure[35, 36]. These electric signals, for strong earthquakes with magnitude 6.5 or larger, are also accompanied by detectable

TABLE I: The values of S, κ_1, S_- for the electric signals presented in Fig.5.

Date recorded	S	κ_1	S_-
Feb 8, 2007	0.067±0.007	0.074±0.007	0.079±0.007
Apr 23, 2007	0.071±0.005	0.069±0.003	0.066±0.005
Apr 21, 2007	0.072±0.003	0.067±0.003	0.069±0.003
Nov 7, 2007	0.070±0.005	0.065±0.005	0.070±0.005

magnetic field variations[37, 38, 39, 40]. Actually, the analysis of the original time series of the SES activities have been shown to obey a $1/f$-behavior[41, 42].

The $1/f^a$ behavior has been well understood on the basis of dynamic scaling observed at *equilibrium* critical points where the power-law correlations in time stem from the infinite-range correlations in space (see Ref.[2] and references therein). Most of the observations mentioned above, however, refer to *nonequilibrium* phenomena for which -despite some challenging theoretical attempts[16, 17, 18, 19]- possible *generic* mechanisms leading to scale invariant fluctuations have not yet been identified. In other words, despite its ubiquity, there is no yet universal explanation about the phenomenon of the $1/f^a$ behavior. Opinions have been expressed (e.g., see Ref.[13]) that it does not arise as a consequence of particular physical interactions, but it is a generic manifestation of complex systems.

It has been recently shown[41, 50, 51, 52, 53, 54, 55, 56, 57, 58, 59, 60, 61] that novel dynamic features hidden behind the time series of complex systems can emerge if we analyze them in terms of a newly introduced time domain, termed natural time χ (see below). It seems that this analysis enables the study of the dynamic evolution of a complex system and identifies when the system enters a critical stage. Natural time domain is optimal[62] for enhancing the signal's localization in the time frequency space, which conforms to the desire to reduce uncertainty and extract signal information as much as possible. In a time series comprising N events, the *natural time* χ_k =

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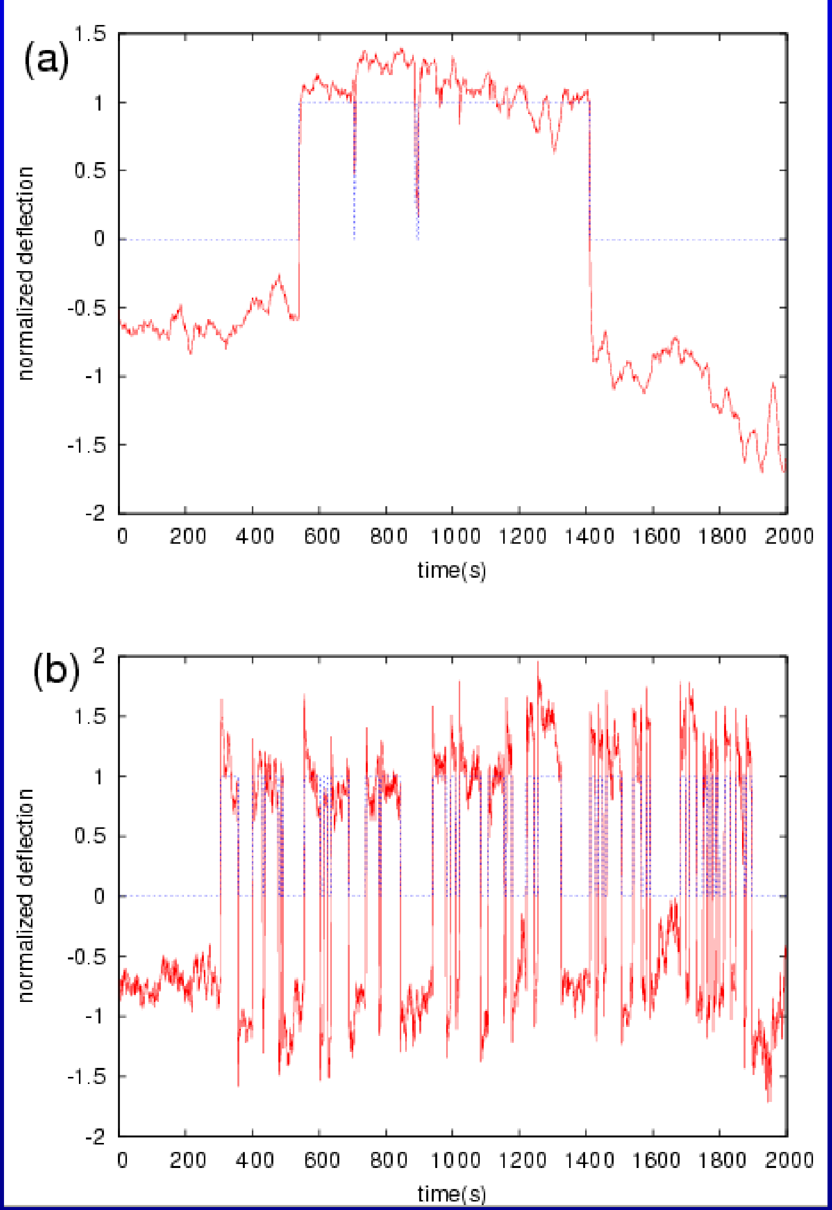
The first page of the article by P. Varotsos, N. Sarlis and E Skordas that was publicised on February 1, 2008 on the scientific website of the Library at Cornell University.

as follows (see Fig.16): One SES activity at PAT on 10 January, 2008 and another one on 14 January, 2008 at the station PIR located in western Greece, see Fig.13 (cf. The configuration of the measuring dipoles in the latter station is described in detail in the EPAPS document of Ref.[60]). Their subsequent seismicities are currently studied along the lines explained above considering the evolving seismicity in the following areas: Concerning the former SES activity at PAT the areas depicted in Fig.13, while for the one at PIR on 14 January, 2008, the subsequent seismicity is studied in the area B of Fig.9 as well as in the larger area $\boxed{N_{36.0}^{38.6}E_{20.0}^{22.5}}$ and in the one surrounding the epicenter[69] (36^oN 23^oE).

Page 12 of the article publicised on February 1, 2008. See the section shown by the arrow, which reports that **two sets of new preseismic signals** (**SES activities**) were recorded on 10 and 14 January at the stations PAT and PIR, respectively



The preseismic electric signals recorded at the stations PAT [(a) above] and PIR [(b) below] on 10 and 14 January respectively, as publicised on February 1, 2008.

ΠΡΟΣΕΙΣΜΙΚΕΣ ΔΟΝΗΣΕΙΣ ΚΑΙ ΠΑΛΙ ΑΠΟ ΤΗΝ ΟΜΑΔΑ ΒΑΝ

ΕΘΝΟΣ 10-2-08

Πρόβλεψη-μυστήριο για σεισμό 6 Ρίχτερ

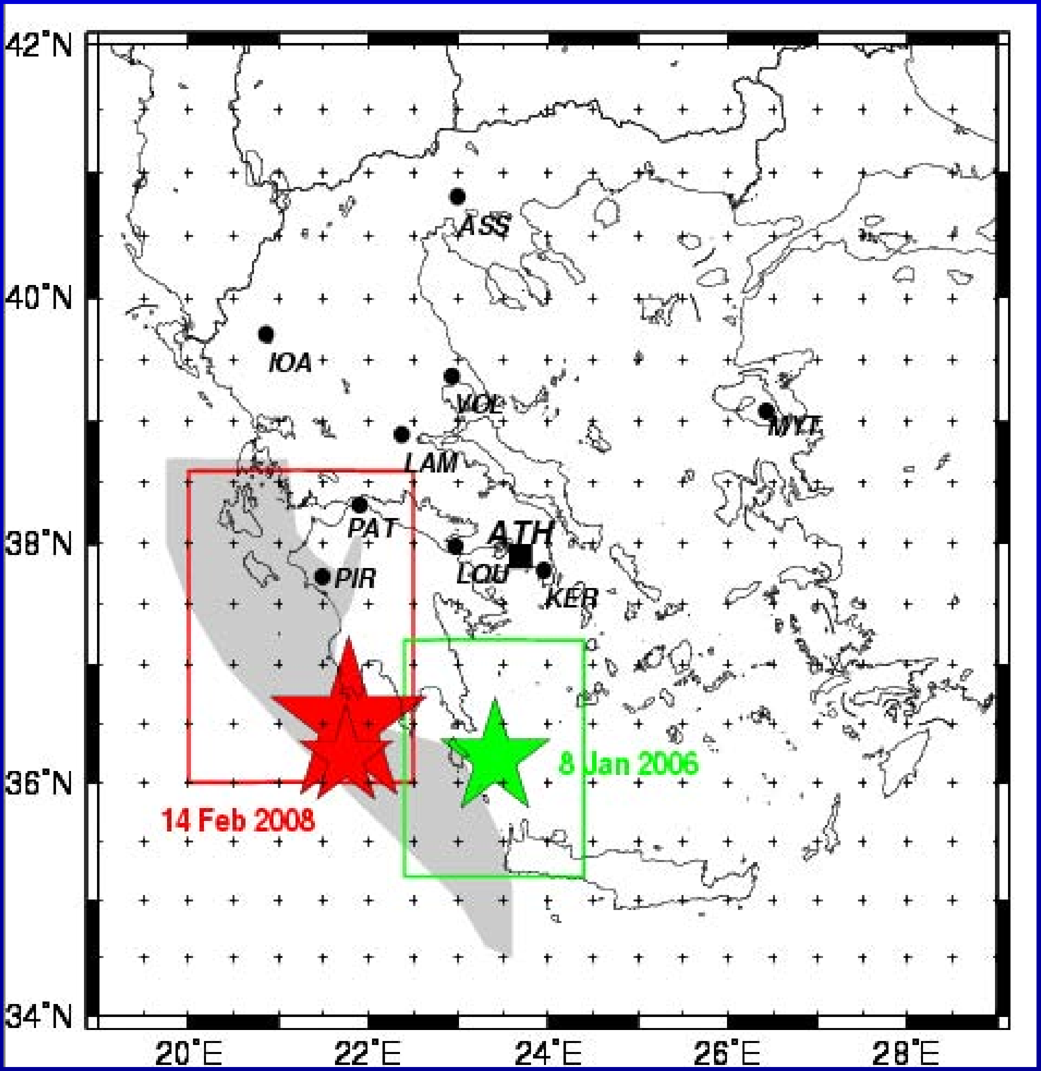
Του ΓΙΑΝΝΗ ΚΡΗΤΙΚΟΥ

Οι προγνώσεις σεισμών της ομάδας ΒΑΝ και του καθηγητή Παναγιώτη Βαρώτσου, αντικείμενο έντονης επιστημονικής διαμάχης πριν από χρόνια, έρχονται ξανά σήμερα στο προσκήνιο. Με νέα ωστόσο δεδομένα, τα οποία εδράζονται στη συνεργασία με κορυφαίο αμερικανικό πανεπιστήμιο, αλλά και σε συνεχείς επιβεβαιώσεις των προβλέψεων μέσα στο 2007. ▶ ΣΕΛ. 36 - 37

ΕΝΗΜΕΡΩΝΟΥΝ ΚΟΡΥΦΑΙΟ ΑΜΕΡΙΚΑΝΙΚΟ ΠΑΝΕΠΙΣΤΗΜΙΟ

Εχουν δώσει πρόγνωση για 4 σεισμούς που έχουν επιβεβαιωθεί και τώρα περιμένουν τον πέμπτο...

The front page of the newspaper ETHNOS on Sunday February 10, 2008 entitled "*Forecast-mystery for an earthquake of 6 Richter*". Furthermore, the publication of this newspaper wrote *"…a strong earthquake greater than 6.0 Richter is imminent"*



The **left rectangle outlined in red** is described on page 12 of the article released on February 1, 2008 **as being the most likely for the upcoming earthquake**

Eos, Vol. 89, No. 39, 23 September 2008

NEWS

The Prediction of Two Large Earthquakes in Greece

PAGE 363

The VAN experimental method of short-term earthquake prediction (named after the initials of three Greek physicists, Panayiotis Varotsos, Kessar Alexopoulos, and Konstantine Nomicos) has been used to monitor preseismic electric signals since the 1980s [see *Varotsos*, 2005]. From observed telluric current signals, called seismic electric signals (SES), the epicentral area, magnitude, and occurrence time of an impending earthquake are estimated. SES are interpreted as having been emitted when the focal region in which the earthquake in question could occur has entered the critical regime (i.e., a stage close to the rupture).

The VAN method recently reached the stage of possibly enabling the narrowing of the time window of earthquake prediction to the order of a few days. This narrowing is made possible by the use of a new method called "natural time analysis." This analysis has been developed to identify the time when a dynamic system (i.e., a system evolving with time) exhibits behavior similar to a phase change [*Varotsos et al.*, 2008, and references therein]. On the hypothesis that the main shock earthquake is a critical phenomenon, when SES activity is observed, natural time analysis is conducted on the seismicities of small earthquakes in the suspected future epicentral area solely by considering their order of occurrence and the energy emitted by each of them. The term natural time analysis stems from the disregard of the conventional time of the earthquakes' occurrence. It has been found that such an analysis enables the identification of the time of the main shock usually within a few days before it occurs (see P. Varotsos et al., Seismic electric signals and 1/f "noise" in natural time, at http://arxiv.org/abs/ 0711.3766).

On 14 February 2008, a large earthquake (U.S. Geological Survey M=6.9) and its probable aftershock (M=6.2) occurred in the Ionian Sea close to the region of southwestern Peloponnese, in Greece. The paper by P. Varotsos et al. (http://arxiv.org/abs/0711.3766), which appeared 2 weeks earlier (1 February 2008), reported that new electric signals were registered on 14 January at the Pirgos VAN electrotelluric station in western Greece, the earthquake for which, however, had not yet occurred. The report also indicated that on the basis of the recorded signal amplitude, the magnitude of the impending earthquake had been expected to be more than 6 and that the epicenter would be inside the area with coordinates 36.0°–38.6°N, 20.0°–22.5°E, i.e., approximately in a 250 × 260 square kilometer area in southwestern Peloponnese.

On 10 February 2008, an article on the front page of the Greek newspaper *Ethnos* announced that a magnitude 6 earthquake would occur imminently in the predicted area. Four days later, on 14 February, the two earthquakes occurred inside the expected area. The first one, the largest in Greece since 1983, was also felt in some adjacent countries. This was a case where prediction by the VAN method was documented in a scientific publication as well as in the public media well before the main shock occurred.

References

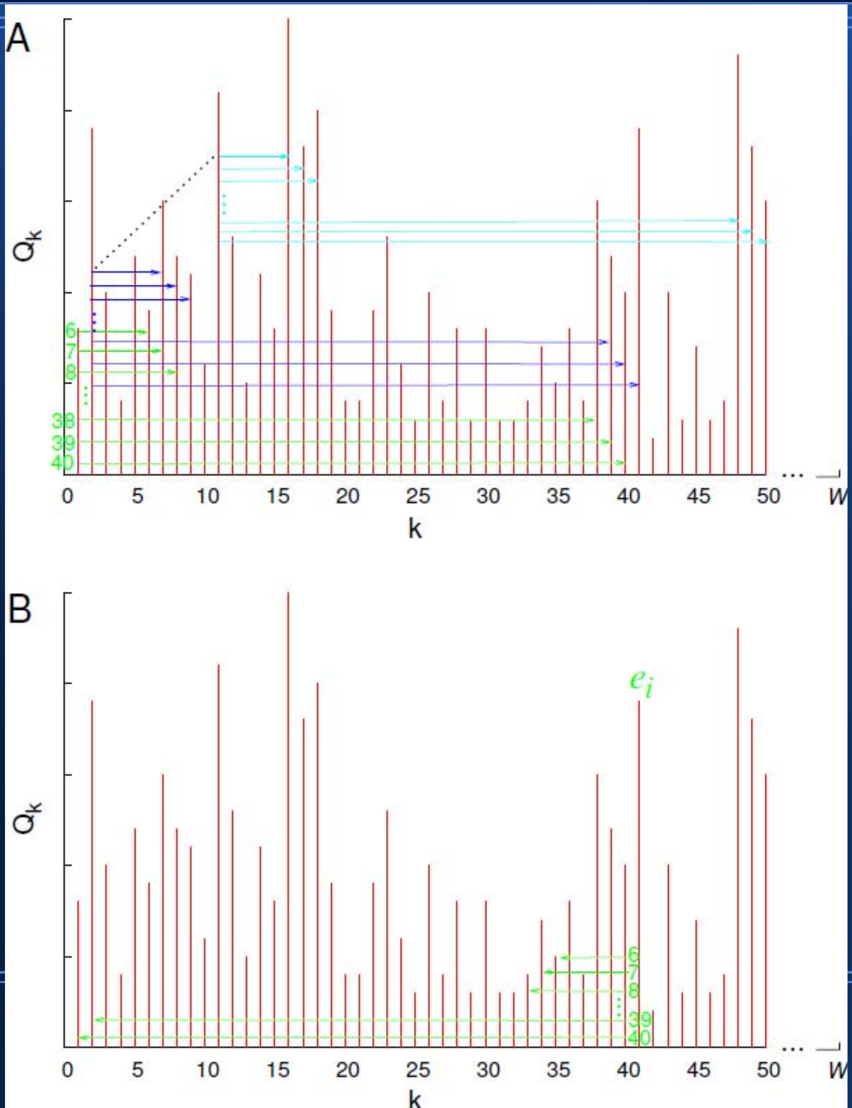
Varotsos, P. (2005), *The Physics of Seismic Electric Signals*, TerraPub, Tokyo.

Varotsos, P. A., N. V. Sarlis, E. S. Skordas, and M. S. Lazaridou (2008), Fluctuations, under time reversal, of the natural time and the entropy distinguish similar looking electric signals of different dynamics, *J. Appl. Phys.*, *103*, 014906, doi:10.1063/1.2827363.

—SEIYA UYEDA, Earthquake Prediction Research Center, Tokai University, Tokyo, Japan; and MASASHI KAMOGAWA, Department of Physics, Tokyo Gakugei University, Tokyo, Japan; E-mail: kamogawa@u-gakugei.ac.jp

The article of Professors SEIYA UYEDA and MASASHI KAMOGAWA in the journal *EOS* of the American Geophysical Union, on 23 September 2008 .

Natural time analysis of seismological catalogs



Two techniques

(A) A natural time window comprising 6 to 40 EQs sliding event by event through an excerpt of a seismic catalog leads to various κ_1 values.

(B) We calculate for each EQ e_i (i=41 in the present example) the κ_1 values using the previous 6 to 40 consecutive EQs (in the opposite direction to that in A).

epl A LETTERS JOURNAL EXPLORING THE FRONTIERS OF PHYSICS

September 2010

EPL, 91 (2010) 59001
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Order parameter fluctuations of seismicity in natural time before and after mainshocks

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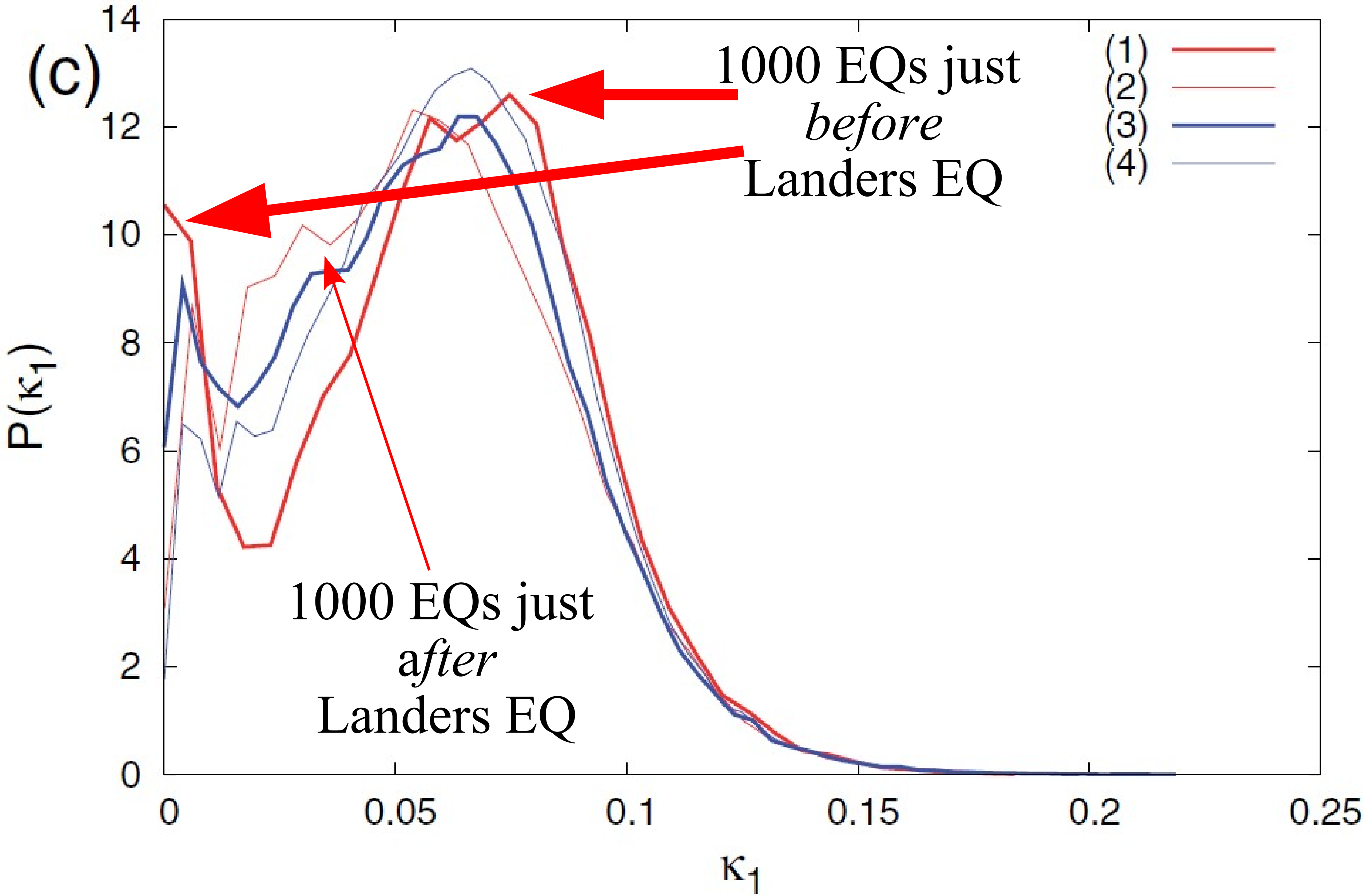
PACS 91.30.Ab – Theory and modeling, computational seismology
PACS 89.75.Da – Systems obeying scaling laws
PACS 95.75.Wx – Time series analysis, time variability

Abstract – It is widely accepted that the observed earthquake scaling laws indicate the proximity of the system to a critical point. Using the order parameter (OP) for seismicity suggested on the basis of natural time as well as the detrended fluctuation analysis of the magnitude time-series, we investigate the behavior of seismicity before and after significant earthquakes. The analysis reveals that the fluctuations of the OP *before* major earthquakes exhibit a characteristic feature which, if quantified properly, may be used as decision variable to predict the occurrence of a large earthquake in the next time step based solely on the magnitudes of previous earthquakes.



(c)
1000 EQs just
before
Landers EQ
1000 EQs just
after
Landers EQ
(1)
(2)
(3)
(4)
$P(\kappa_1)$
κ_1
0
2
4
6
8
10
12
14
0
0.05
0.1
0.15
0.2
0.25

New result!

The variability of κ_1,

$\beta \equiv \sigma(\kappa_1)/\mu(\kappa_1)$,

Exhibits an increase when approaching a main shock.

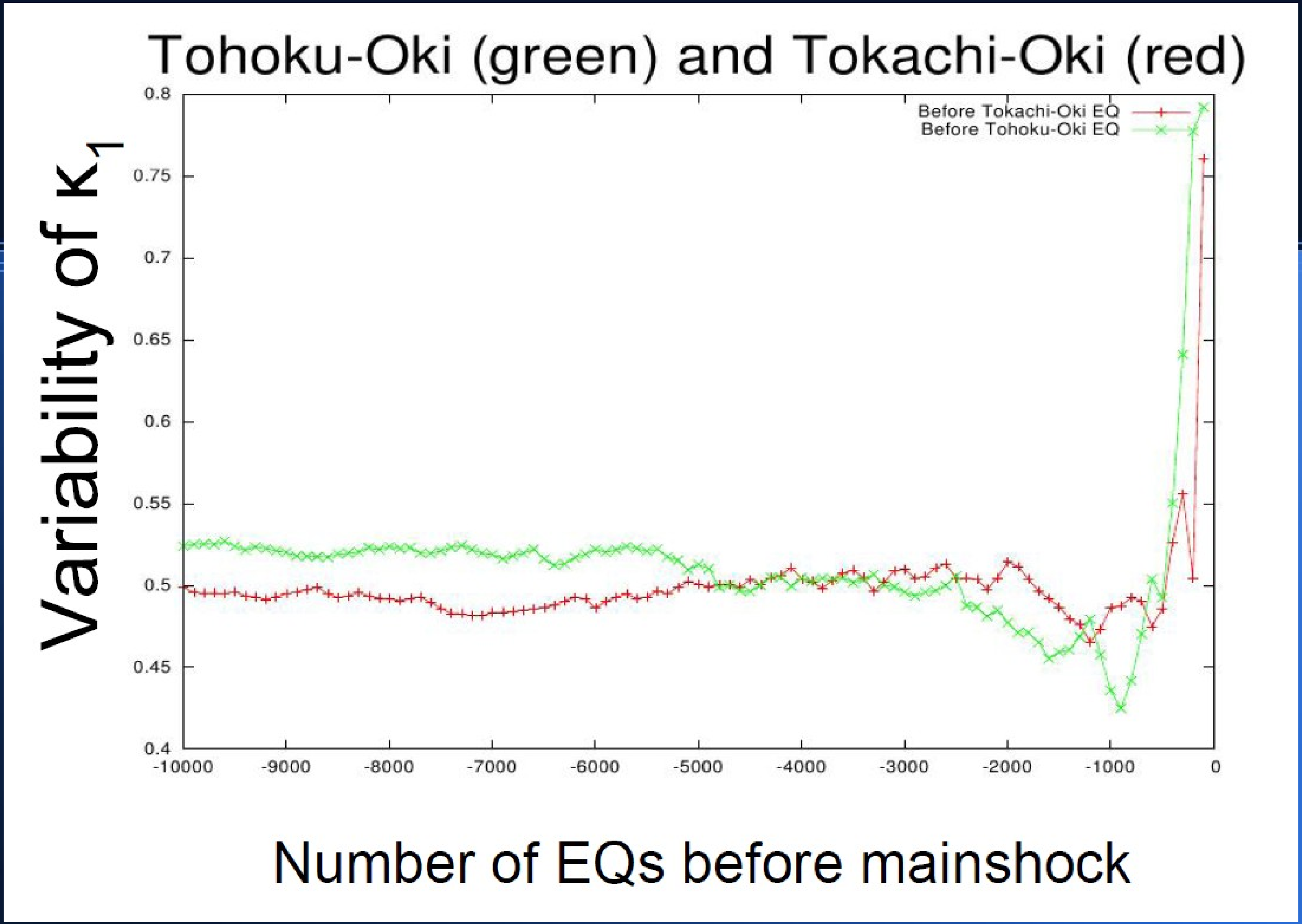


Fig. A6, taken from the book “EARTHQUAKE PREDICTION BY SEISMIC ELECTRIC SIGNALS: The success of the VAN method over thirty years” by Dr Mary Lazaridou-Varotsos just published by *Spinger-Verlag*”

epl A Letters Journal Exploring the Frontiers of Physics

December 2011

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

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received 13 September 2011; accepted in final form 17 October 2011
published online 16 November 2011

PACS 91.30.Ab – Theory and modeling, computational seismology
PACS 89.75.Da – Systems obeying scaling laws
PACS 95.75.Wx – Time series analysis, time variability

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.

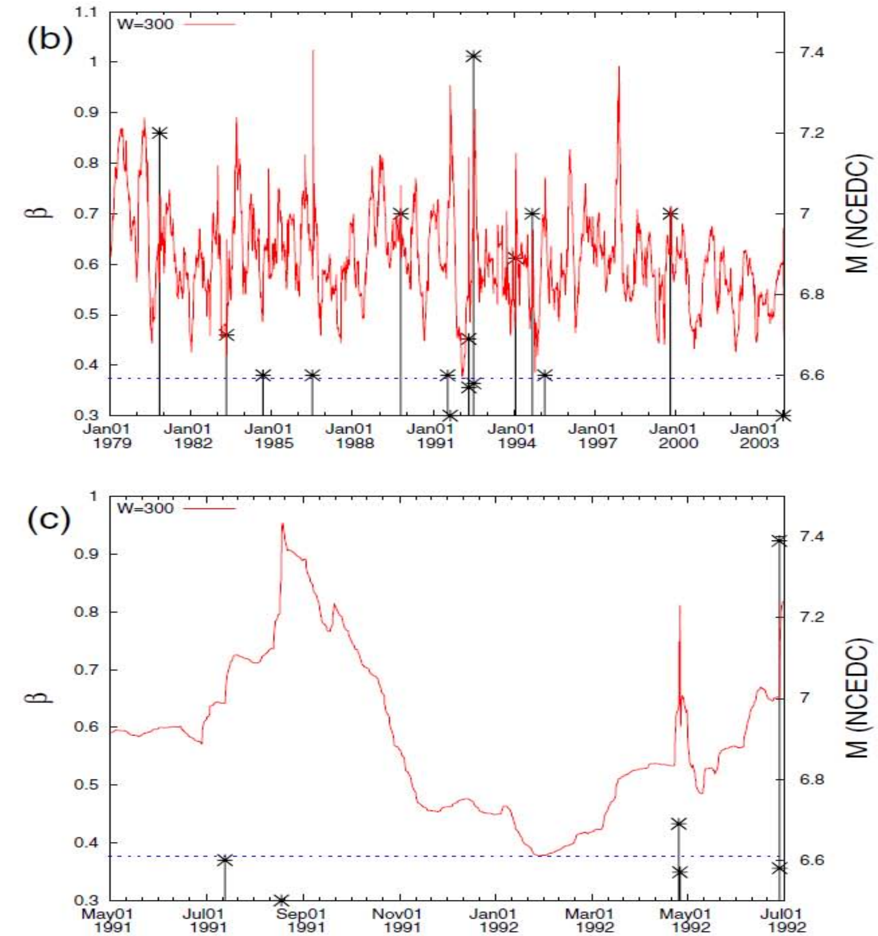

Fig. 1: (Color online) (a) The variability of κ_1 *vs.* the number of events (earthquakes) when a natural time window of length $W = 300$ events is sliding through the NCEDC catalog for the seismicity ($M \geqslant 2.5$) in California during the 25 year period January 1, 1979 to December 31, 2003. The 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.

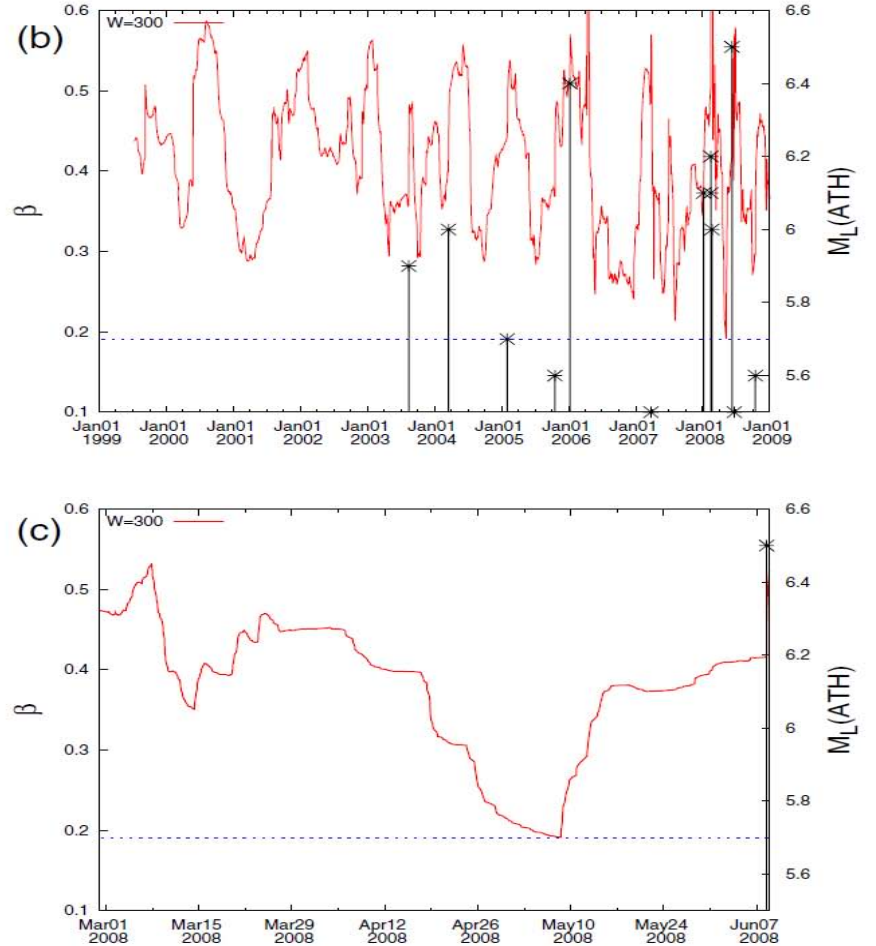

Fig. 2: (Color online) (a) The variability of κ_1 *vs.* the number of events (earthquakes) when a natural time window of length $W = 300$ events is sliding through the GI-NOA catalog for the seismicity ($M_L \geqslant 3.2$) in the area $\mathrm{N}_{34.0}^{39.5}\mathrm{E}_{19.5}^{25.0}$ in Greece during 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.

New result!

The variability of κ_1,

$$\beta \equiv \sigma(\kappa_1)/\mu(\kappa_1),$$

calculated for the specific scale W=300, which corresponds to the average lead time of SES, exhibits a clear minimum before the strongest mainshock.

epl A LETTERS JOURNAL EXPLORING THE FRONTIERS OF PHYSICS

September 2012

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www.epljournal.org

Scale-specific order parameter fluctuations of seismicity before mainshocks: Natural time and Detrended Fluctuation Analysis

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received 16 May 2012; accepted in final form 10 August 2012
published online 11 September 2012

PACS 91.30.Ab – Theory and modeling, computational seismology
PACS 89.75.Da – Systems obeying scaling laws
PACS 95.75.Wx – Time series analysis, time variability

Abstract – The order parameter fluctuations of seismicity are investigated upon considering a natural time window of fixed length sliding through the consecutive earthquakes that occurred in California. We previously found that when this length corresponds to a time period of the order of a few months, the fluctuations exhibit a global minimum before the strongest mainshock. Here, we show that in California, during the twenty five year period 1979–2003, minima of the fluctuations are identified 1 to 5 months before four out of five mainshocks with magnitude $M = 7.0$ or larger as well as before the $M = 6.9$ Northridge earthquake. These minima are accompanied by minima of the exponent α of the Detrended Fluctuation Analysis (DFA) of the earthquake magnitude time series, which since $\alpha < 0.5$ indicate anticorrelated behavior. These results of DFA alone cannot serve for prediction purposes, but do so when combined with the aforementioned minima in the fluctuations of the order parameter of seismicity identified in natural time analysis.

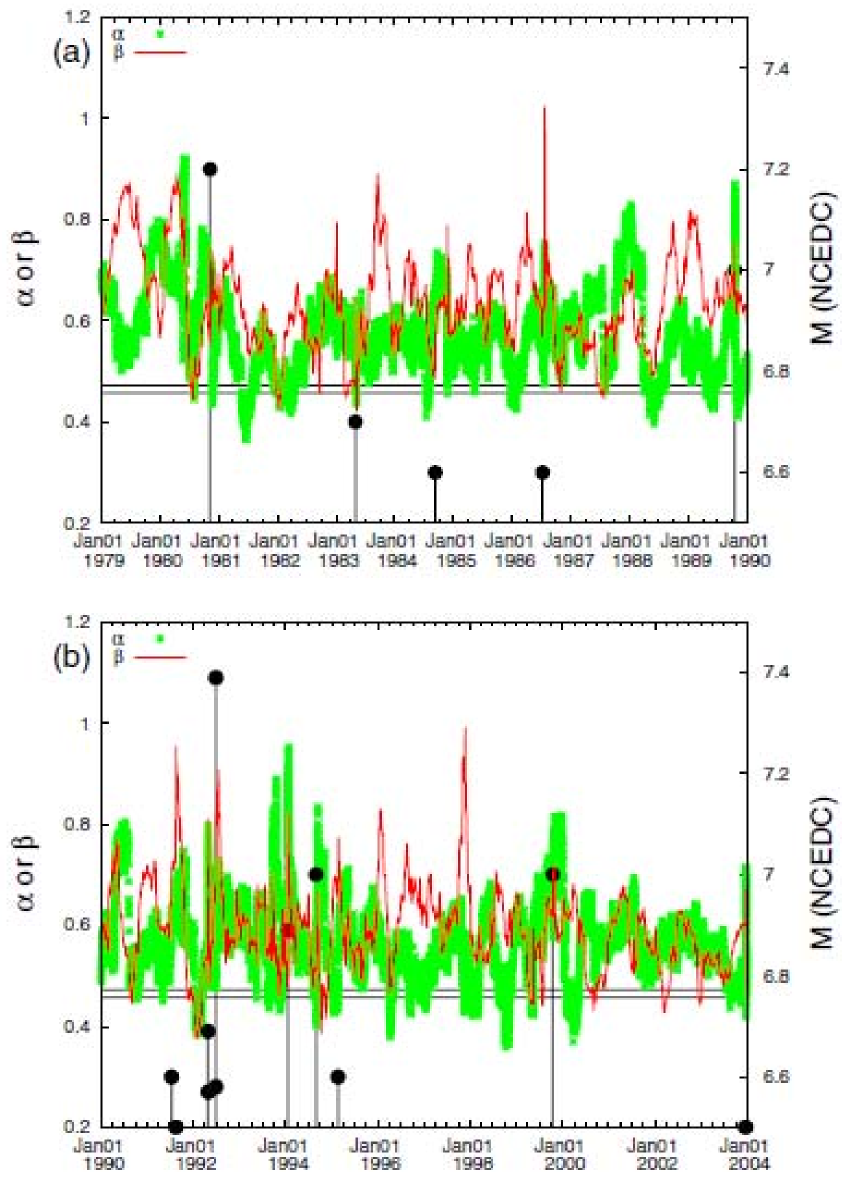
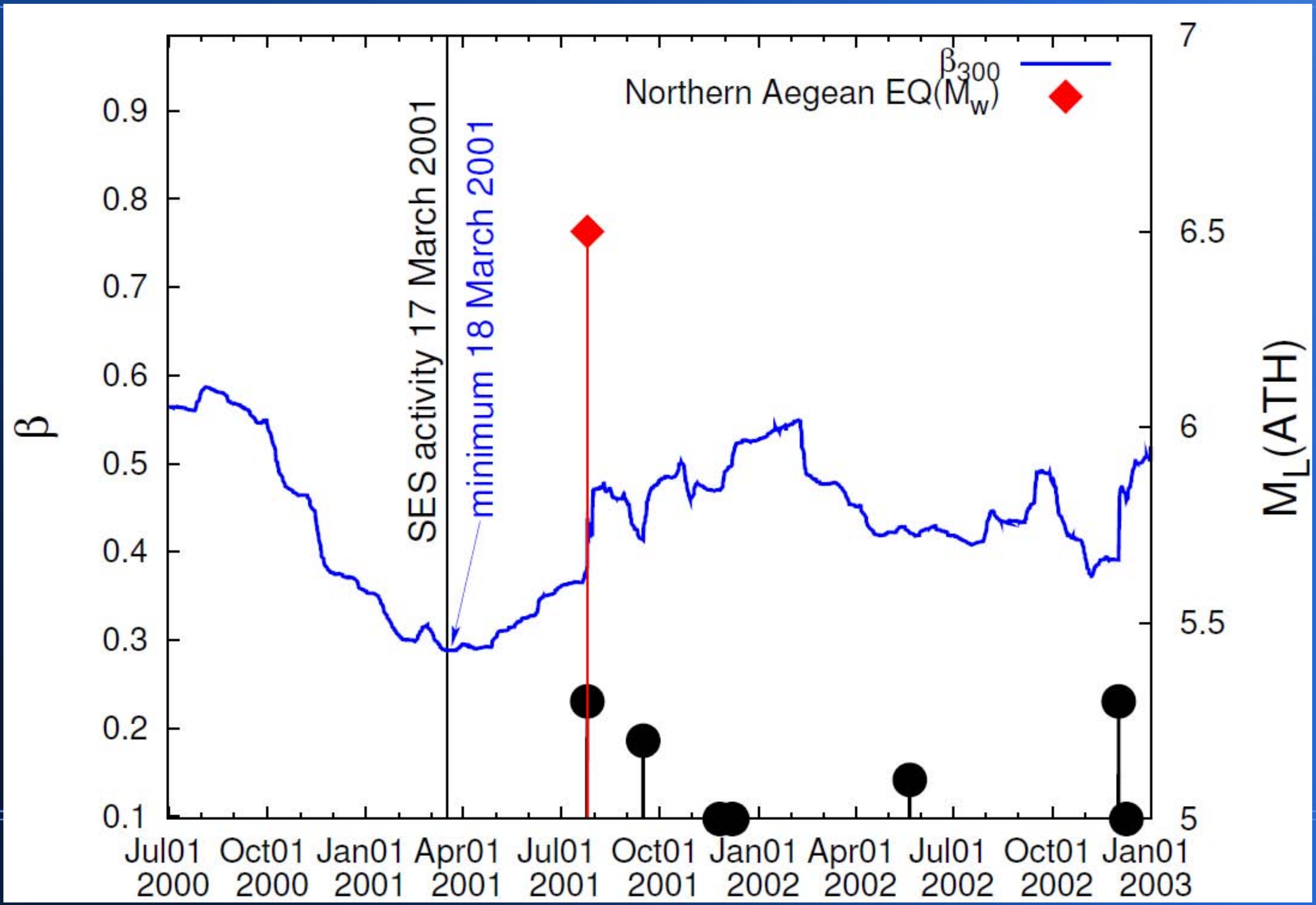


Fig. 3: (Color online) The same as in fig. 2, but the relevant quantities here are plotted *vs.* the conventional time.

Table 1: All major EQs with $M \geqslant 7.0$ within $N_{31.7}^{45.7} W_{127.5}^{112.1}$ during the period 1979–2003. The $M = 6.9$ Northridge earthquake is also included in italics. The values of minima observed for the variability β of κ_1 and the DFA exponent α together with the dates of their observation, in parentheses, are also inserted. The lead time Δt for each case is shown in the last column.

EQ Date	LAT	LON	M (NCEDC)	EQ Name	β	α	Δt (months)
1980-11-08	41.08	−124.62	7.2	Eureka	0.444 (1980-08-01)	0.445 (1980-08-01)	≈ 3
1989-10-18	37.04	−121.88	7.0	Loma Prieta	–	–	–
1992-06-28	34.19	−116.46	7.4	Landers	0.378 (1992-01-28)	0.383 (1992-02-02)	$\leqslant 5$
1994-01-17	*34.23*	*−118.55*	*6.9*	*Northridge*	*0.459 (1993-11-14)*	*0.431 (1993-11-14)*	$\approx$ *2*
1994-09-01	40.41	−126.30	7.0	Mendocino fault	0.472 (1994-08-01)	0.458 (1994-08-09)	≈ 1
1999-10-16	34.60	−116.34	7.0	Hector Mine	0.444 (1999-05-14)	0.422 (1999-05-15)	≈ 5

The recording of SES activities are shown to be accompanied by characteristic changes of *independent geophysical data*



New result!

The minimum of the variability of κ_1,
$\beta \equiv \sigma(\kappa_1)/\mu(\kappa_1)$, calculated for
the specific scale W=300 (which
corresponds to the lead time of SES)
occurs almost simultaneously
with the SES activity initiation

The Izu Islands volcanic-seismic swarm activity in 2000

Uyeda, S., Hayakawa, M., Nagao, T., Molchanov, O., Hattori, K., Orihara, Y., Gotoh, K., Akinaga, Y., Tanaka, H., 2002. Electric and magnetic phenomena observed before the volcano-seismic activity in 2000 in the Izu Island region, Japan. *Proc. Natl. Acad. Sci. USA* 99, 7352–7355.

Uyeda, S., Kamogawa, M., Tanaka, H., 2009. Analysis of electrical activity and seismicity in the natural time domain for the volcanic-seismic swarm activity in 2000 in the Izu Island region, Japan. *J. Geophys. Res.* 114, B02310.

The SES activity at Niijima Island, Japan

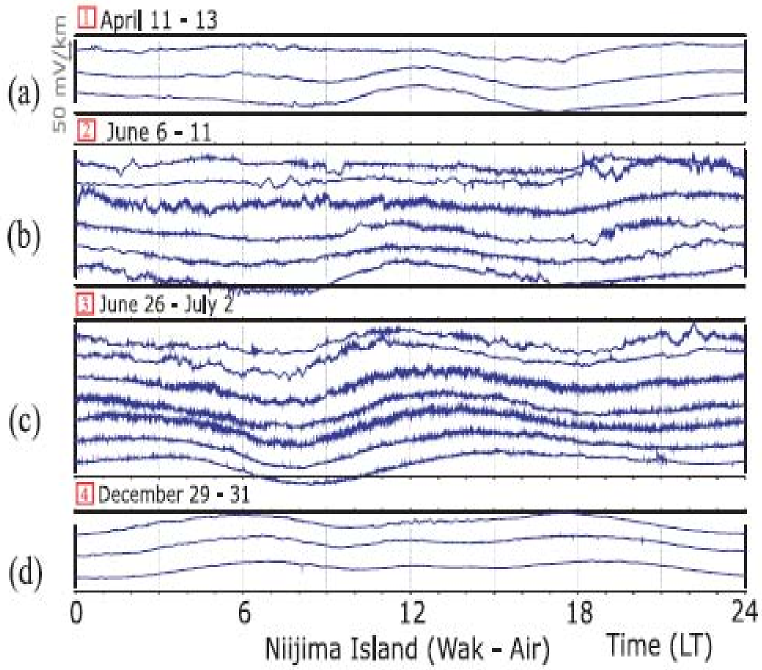


Figure 9. Examples of typical 24-h records of the Wak-Air long dipole potential difference [*Uyeda et al.*, 2002] (50 mV/km scale is indicated on the vertical axis). (a) Before 26 April. Records showed mainly smooth variations only. (b) During 2 months before the onset (26 June) of the seismic swarm activity. Numerous anomalous changes occurred. (c) Just after 26 June. Anomalous changes were more conspicuous. (d) After the cessation of the swarm activity, records resumed usual quietness. Time windows 1, 2, 3, and 4 are indicated in Figure 10 (top).

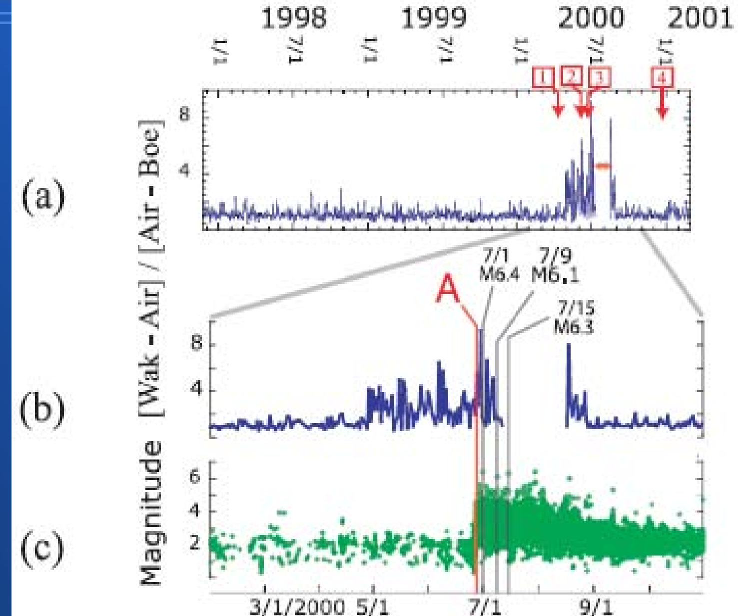


Figure 10. Three year record [*Uyeda et al.*, 2002]. Time change of the 0.01 Hz spectral intensity ratio of geoelectric potential difference at Wak-Air and Air-Boe dipoles, Niijima Island. Anomalous changes started about two months before the seismic swarm (26 June to 29 August). The gap in data was caused by the system failure due to shaking and typhoons in July and August 2000. The numbers 1, 2, 3, and 4 correspond to those in Figure 9. A is the date of the "true coincidence."

Tectonophysics 589 (2013) 116–125

Seismic Electric Signals: An additional fact showing their physical interconnection with seismicity ☆

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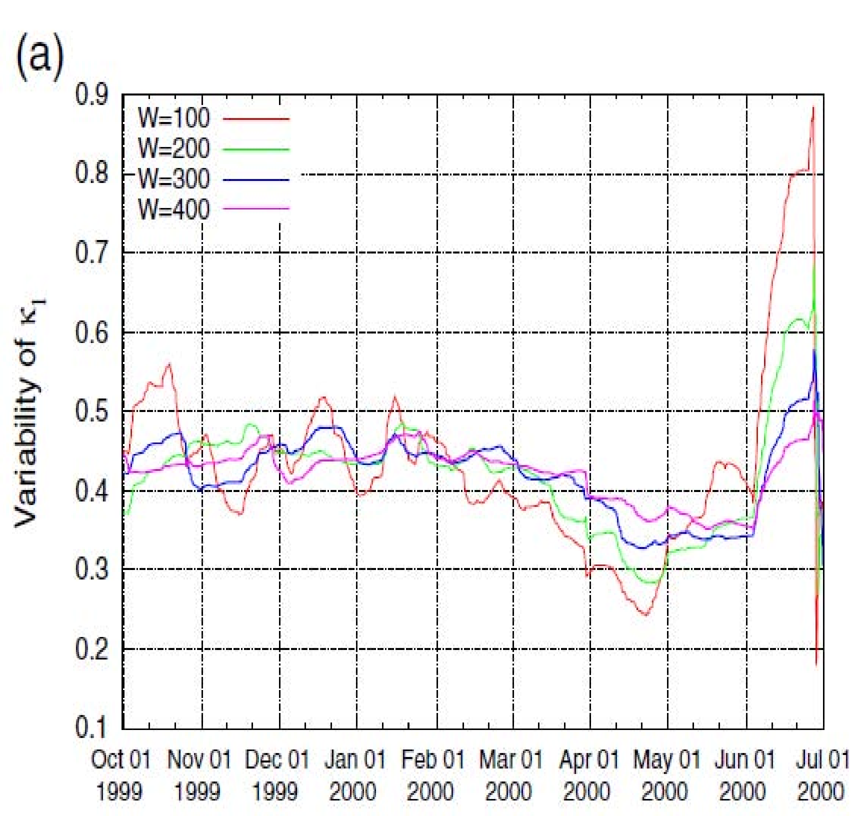
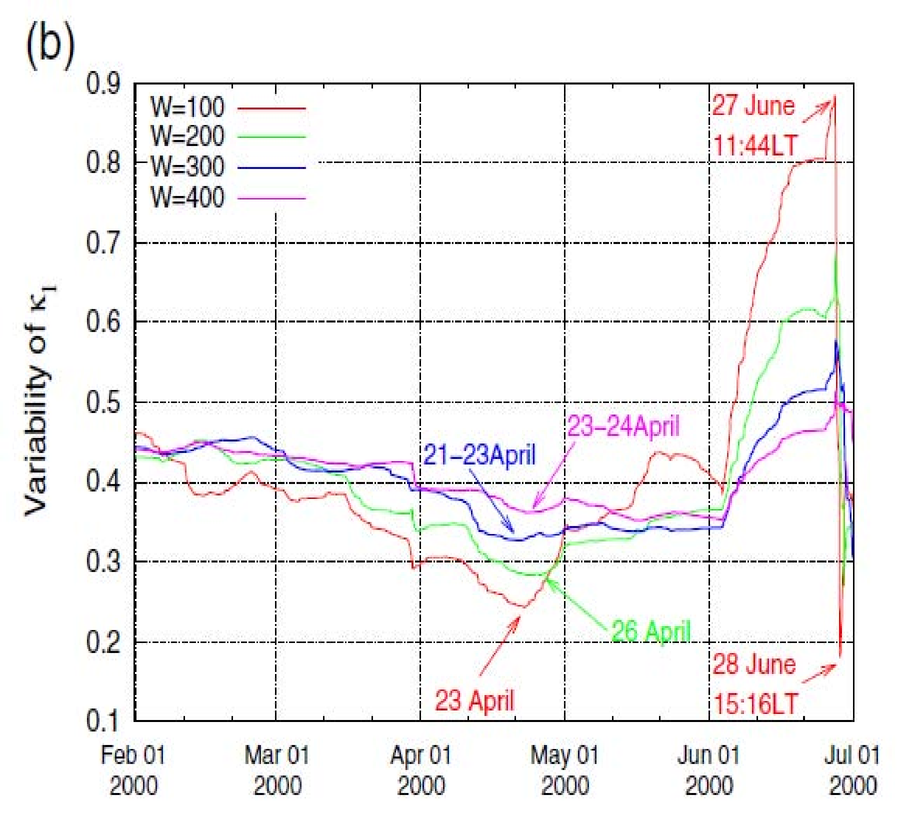
A B S T R A C T

Natural time analysis reveals novel dynamical features hidden behind time series in complex systems. By applying it to the time series of earthquakes, we find that the order parameter of seismicity exhibits a unique change approximately at the date(s) at which Seismic Electric Signals (SES) activities have been reported to initiate. In particular, we show that the fluctuations of the order parameter of seismicity in Japan exhibits a clearly detectable minimum approximately at the time of the initiation of the SES activity observed by Uyeda and coworkers almost two months before the onset of the volcanic-seismic swarm activity in 2000 in the Izu Island region, Japan. To the best of our knowledge, this is the first time that, well before the occurrence of major earthquakes, anomalous changes are found to appear almost simultaneously in two independent datasets of different geophysical observables (geoelectrical measurements, seismicity). In addition, we show that these two phenomena are also linked closely in space.

☆ On the occasion of the 80th birthday of Professor Seiya Uyeda.





The variability of the order parameter κ_1 of seismicity versus the conventional time (LT) for natural time window lengths W=100 events (red), W=200 events (green), W=300 events (blue) and W=400 events (magenta) during the period from (a):1 October 1999 to 1 July 2000 and (b):1 February 2000 to 1 July 2000 until just before the occurrence of the M6.4 EQ on 1 July 2000. The JMA catalog was used with magnitude threshold M > 3.4 (Varotsos et al, Tectonophysics 589, 116-125, 2013)

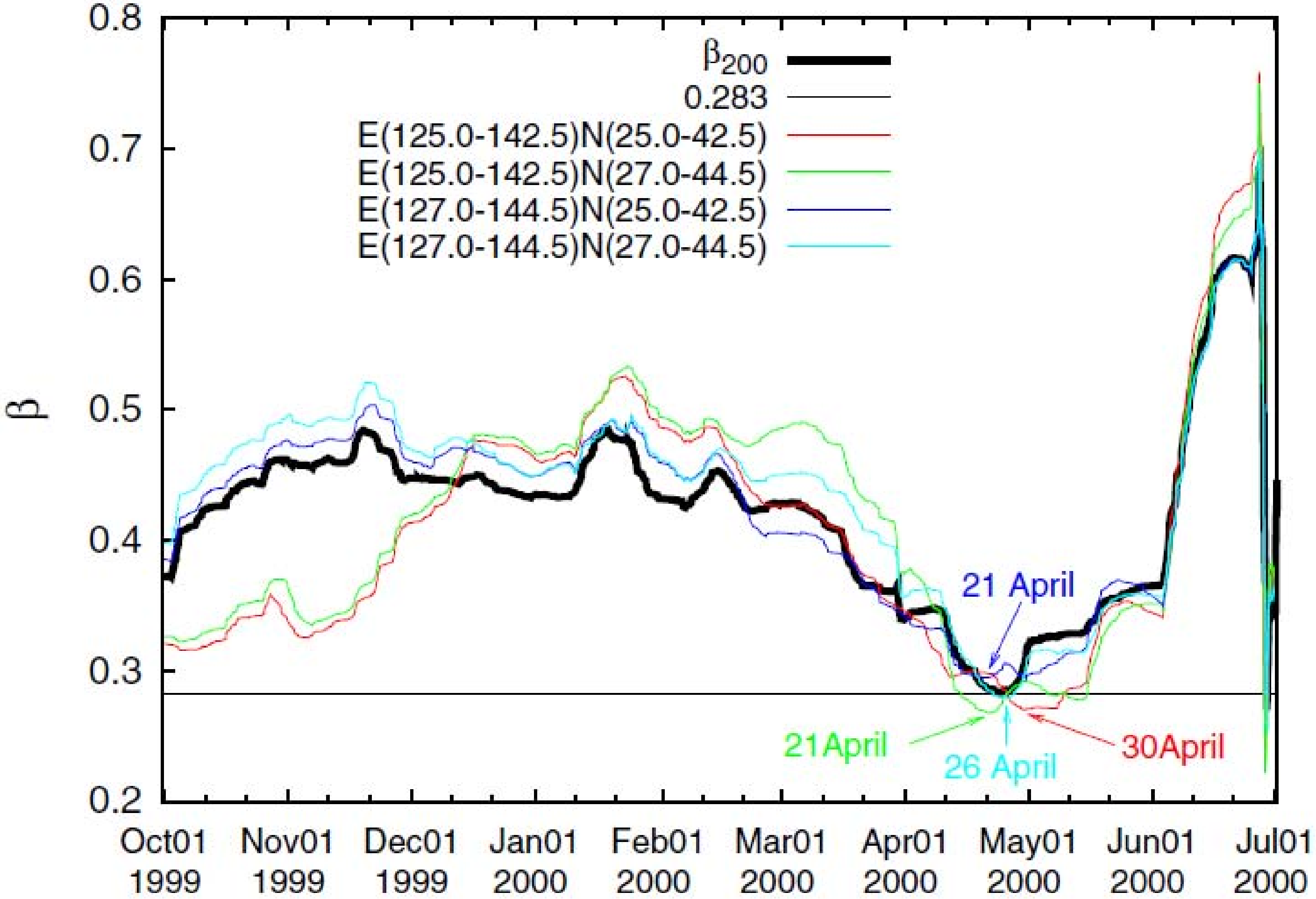
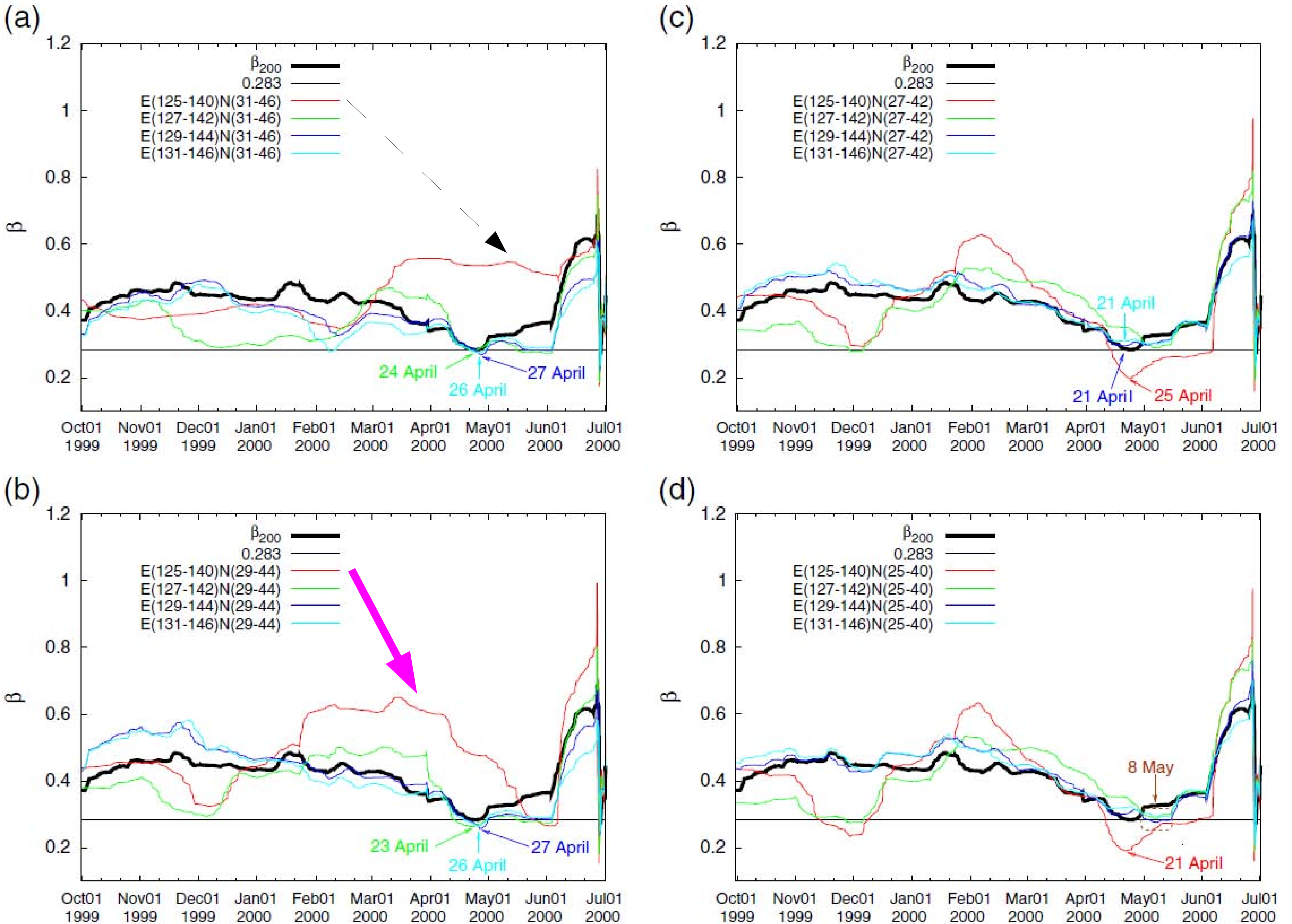


Fig. 4. The same as Fig. 3, but for a sliding area window 17.5°×17.5°. The results shown correspond to the following areas: $N^{42.5}_{25.0}E^{142.5}_{125.0}$ (red), $N^{44.5}_{27.0}E^{142.5}_{125.0}$ (green), $N^{42.5}_{25.0}E^{144.5}_{127.0}$ (blue) and $N^{44.5}_{27.0}E^{144.5}_{127.0}$ (cyan).

52


(a)
β200
0.283
E(125-140)N(31-46)
E(127-142)N(31-46)
E(129-144)N(31-46)
E(131-146)N(31-46)
24 April
26 April
27 April
(c)
E(125-140)N(27-42)
E(127-142)N(27-42)
E(129-144)N(27-42)
E(131-146)N(27-42)
21 April
21 April
25 April
(b)
E(125-140)N(29-44)
E(127-142)N(29-44)
E(129-144)N(29-44)
E(131-146)N(29-44)
23 April
26 April
27 April
(d)
E(125-140)N(25-40)
E(127-142)N(25-40)
E(129-144)N(25-40)
E(131-146)N(25-40)
8 May
21 April
β
Oct01 1999
Nov01 1999
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Mar01 2000
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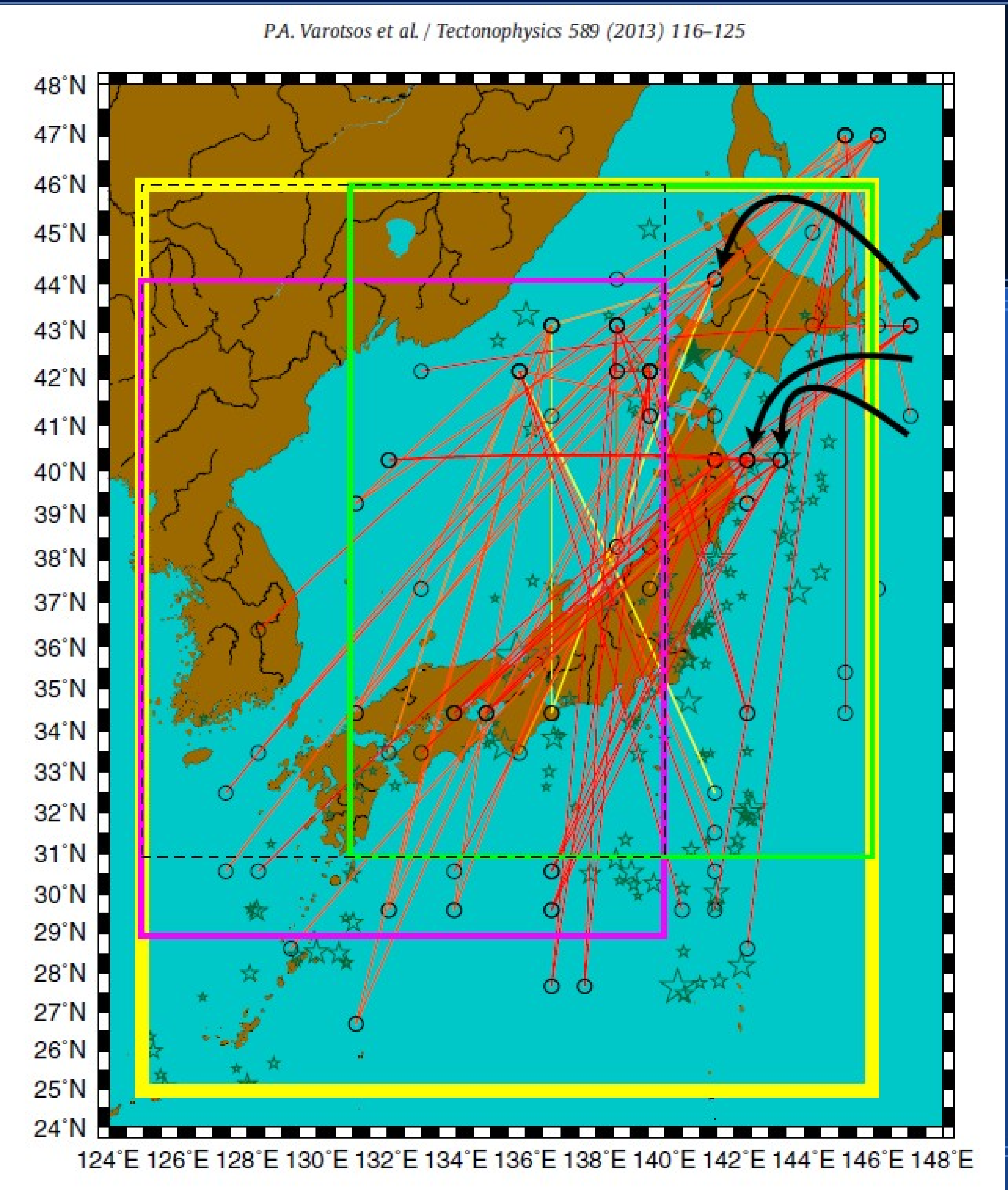
May01 2000
Jun01 2000
Jul01 2000



The nodes and links are taken from:

Tenenbaum, J.N., Havlin, S., Stanley, H.E., Earthquake networks based on similar activity patterns *Phys. Rev. E* **86**, 046107 (2012).

The stars show the epicenters of the 200 events when the ending of the natural time window of length W=200 lies on the minimum of β on 26 April 2000. The yellow rectangle boundaries mark the area used in the present analysis.

The two areas (out of 16): “broken black” and “solid purple” of 15°×15° do not exhibit a minimumof β at a date close to 26 April 2000,while the “solid green” does so.

Conclusion

If we consider a wide area (15°×15°) not containing strong nodes and links the phenomenon studied *cannot* be seen in these wide areas.

This strengthens the existence of strong links representing large correlations between patterns in locations separated by more than 1000km as well the stability of these links over time as found by Tenenbaum, Havlin and Stanley, *Phys. Rev. E* **86**, 046107 (2012)

[cf . the time period of the two studies is different]

Acknowledgement

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Thank you!

Thank you!

PRL 94, 170601 (2005) PHYSICAL REVIEW LETTERS week ending 6 MAY 2005

Origin of the Usefulness of the Natural-Time Representation of Complex Time Series

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[2]Solid State Section, Physics Department, University of Athens, Panepistimiopolis, Zografos 157 84, Athens, Greece

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[4]Earthquake Prediction Research Center, Tokai University, Shizuoka 424-8610, Japan

(Received 3 December 2004; published 2 May 2005)

The concept of natural time turned out to be useful in revealing dynamical features behind complex time series including electrocardiograms, ionic current fluctuations of membrane channels, seismic electric signals, and seismic event correlation. However, the origin of this empirical usefulness is yet to be clarified. Here, it is shown that this time domain is in fact optimal for enhancing the signals in time-frequency space by employing the Wigner function and measuring its localization property.

DOI: 10.1103/PhysRevLett.94.170601 PACS numbers: 05.40.−a, 05.45.Tp, 05.90.+m, 87.10.+e

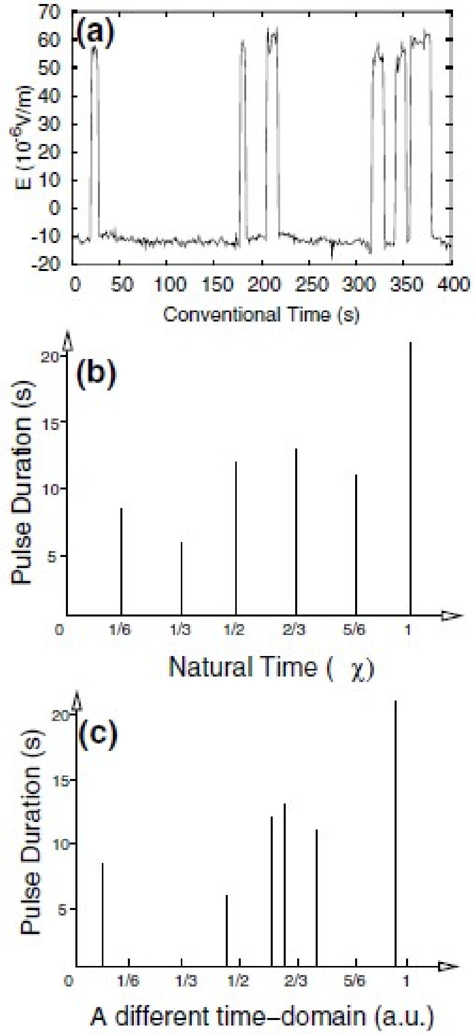


FIG. 1. An example of observed time series of SES activity represented in (a) conventional time, (b) natural time, and (c) a randomly generated time. In (b), the natural time serves as an index of the occurrence of each pulse (reduced by the total number of pulses), while the amplitude is proportional to the duration of each electric pulse [12–15].

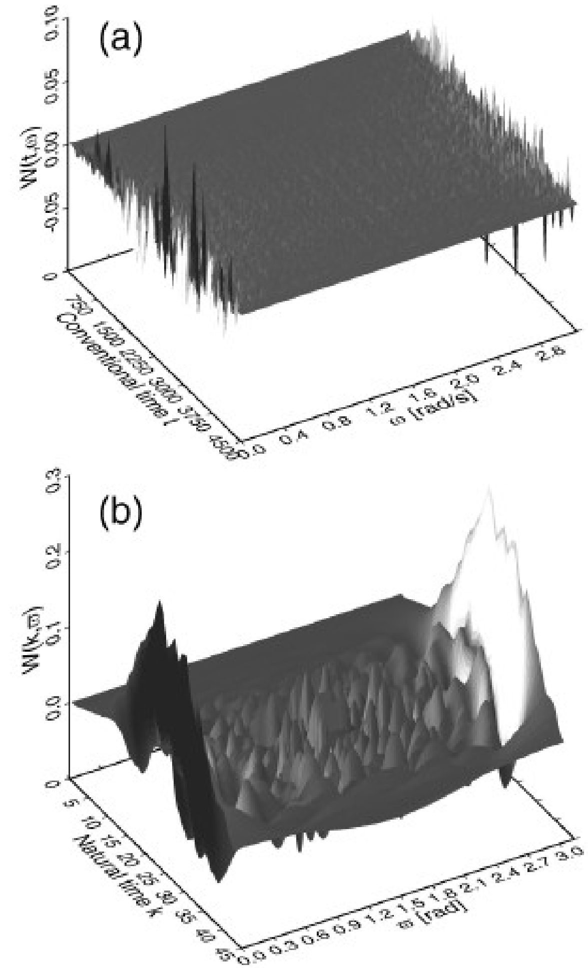


FIG. 2. The plots of the Wigner functions of the SES activity A in Fig. 3 given below in (a) the conventional time domain and (b) the natural-time domain. Significant enhancement of the signal is recognized in the natural-time domain at both edges but mainly in the localized structures in the intermediate region. Note that, instead of χ_k, $N\chi_k = k$ is used (see the text). ω has the unit [rad/sec], whereas $\bar{\omega}$ has [rad].

To quantify the degrees of disorder in the time-frequency spaces with various time domains, we employ, as mentioned, the Tsallis entropy [27] defined by

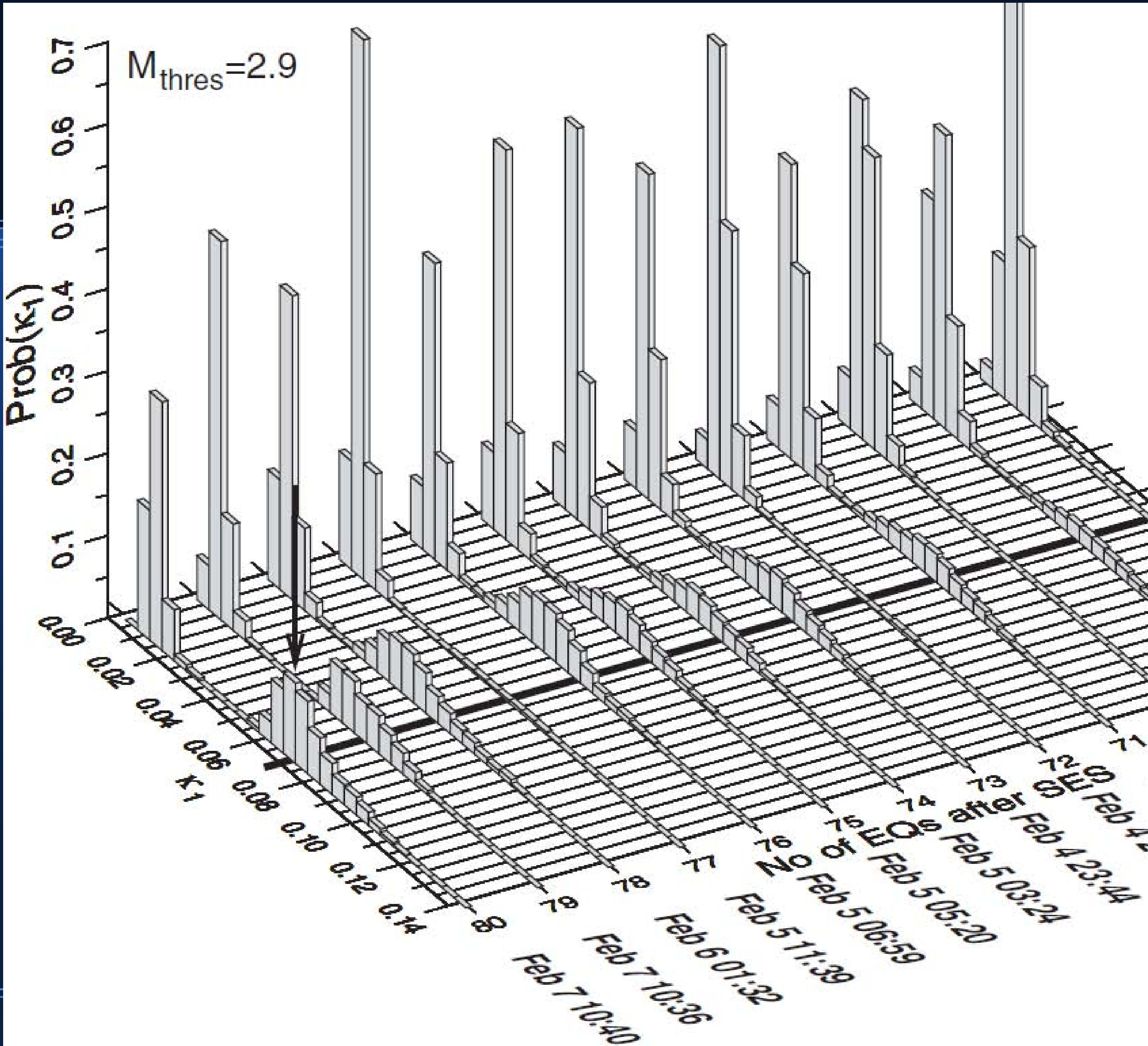
$$S_q = \frac{1}{1-q}\left(\int d\mu W^q - 1\right), \qquad (3)$$

where $\int d\mu$ is the collective notation for integral and sum over the time-frequency space and q is the positive entropic index. In the limit $q \to 1$, this quantity tends to the form of the Boltzmann-Gibbs-Shannon entropy $S = -\int d\mu W \ln W$. This limit cannot however be taken, since the Wigner function is a pseudodistribution and takes negative values, in general. S_q is, however, well defined if q is even. Thus, we propose to use the value

$$q = 2,$$

TABLE I. The number of N pulses and the values of $p(S_2 < S_2^{\mathrm{nat}})$ for the 10 electric signals analyzed. The estimation error is at the most 1.6%.

Signal	N	$p(S_2 < S_2^{\mathrm{nat}})(\%)$
K1	312	3.7
K2	141	6.9
A	43	28.5
U	80	8.1
n6	42	26.0
n5	432	2.8
n4	396	1.6
n3	259	2.7
n2	1080	<0.1
n1	216	5.7



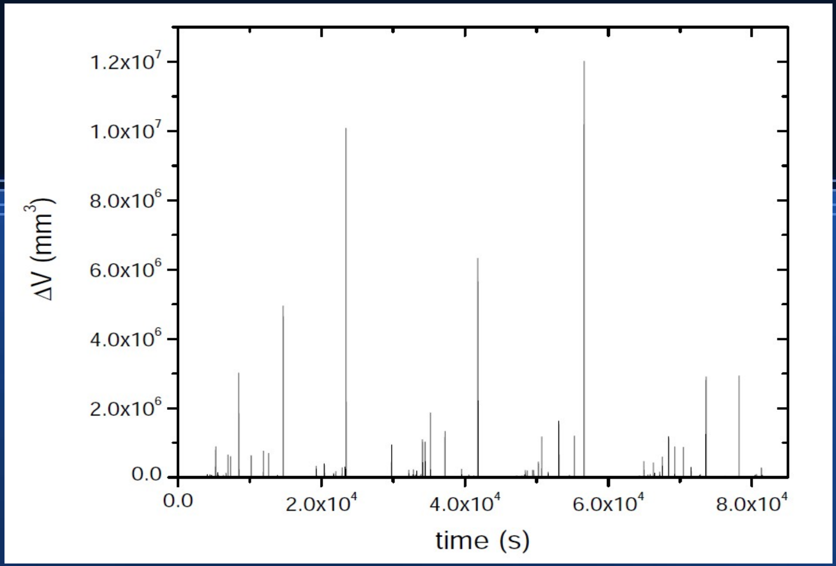
Prob(κ_1) versus κ_1 for the seismicity for (a) $M_{thres} = 2.8$, (b) $M_{thres} = 2.9$, and (c) $M_{thres} = 3.0$ that occurred within the area $N^{38.6}_{36.0}$ $E^{22.5}_{20.0}$ after the SES activity at PIR on January 14, 2008, depicted in Fig. 7.22(b). The simultaneous maxima of Prob(κ_1) versus κ_1 at $\kappa_1 \approx 0.070$, marked with arrows, are observed upon the occurrence of a $M_L = 3.4$ EQ at 10:40 UT on February 7, 2008, with epicenter at 38.37°N 20.32°E.

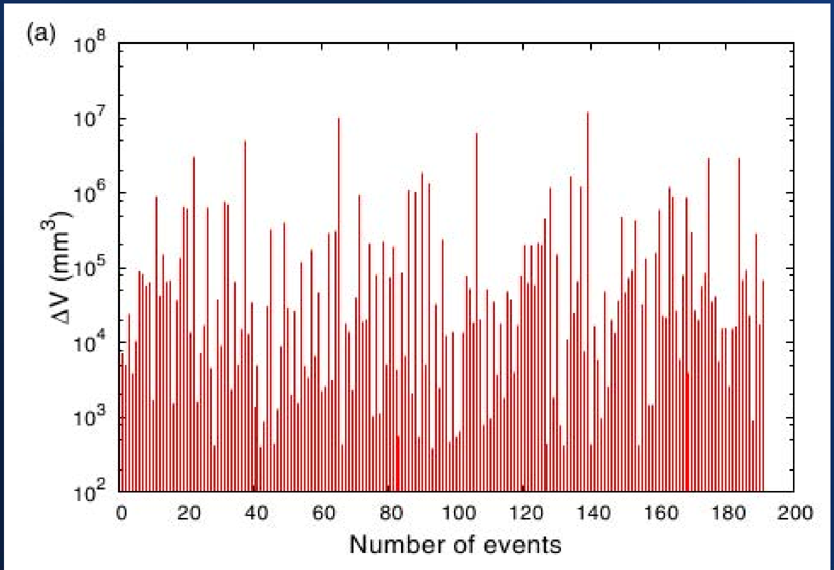
Abstract

Natural time analysis provides a general framework for the study of complex systems. It enables the identification of novel dynamical features hidden behind the time series of complex systems.

Natural time analysis has been shown to extract the maximum information possible in the study of the dynamical evolution of a complex system. It identifies when a system enters a critical stage. Hence, it plays a key role in predicting catastrophic events in general. We review a series of such examples including the analysis of avalanches of the penetration of magnetic flux into thin films of high Tc superconductors, the identification of sudden cardiac death risk, the recognition of electric signals that precede earthquakes and the determination of the time of an impending mainshock. In particular, we review cases of major earthquakes that occurred in Greece, California and Japan.

Avalanches in 3d rice piles approaching SOC



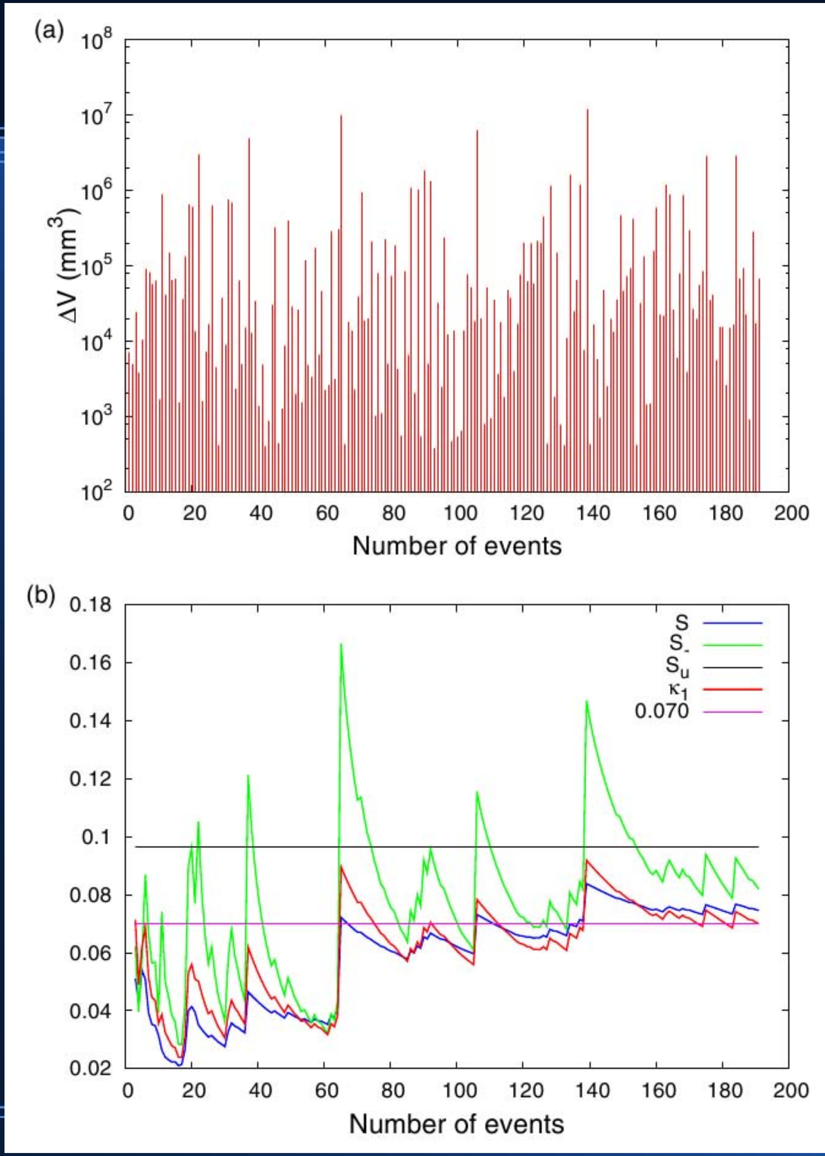


Lorincz K. A., Avalanche dynamics in a three- dimensional pile of rice, PhD Thesis, Vrije Universiteit (Gildeprint Drukkerijen Enschede, Amsterdam, The Netherlands) 2008.

N. V. Sarlis, E. S. Skordas and P. A. Varotsos, Similarity of fluctuations in systems exhibiting Self-Organized Criticality EPL, 96 (2011) 28006.

We express our sincere thanks to Prof. Rinke J. Wijngaarden and Dr. Kinga A. Lőrincz for kindly providing the rice pile data analyzed.

NTA of avalanches in 3d rice piles



EPL, 96 (2011) 28006

κ_1 ($=\langle\chi^2\rangle-\langle\chi\rangle^2$) characterizes signals emitted from critical systems

Seismic Electric Signals activities

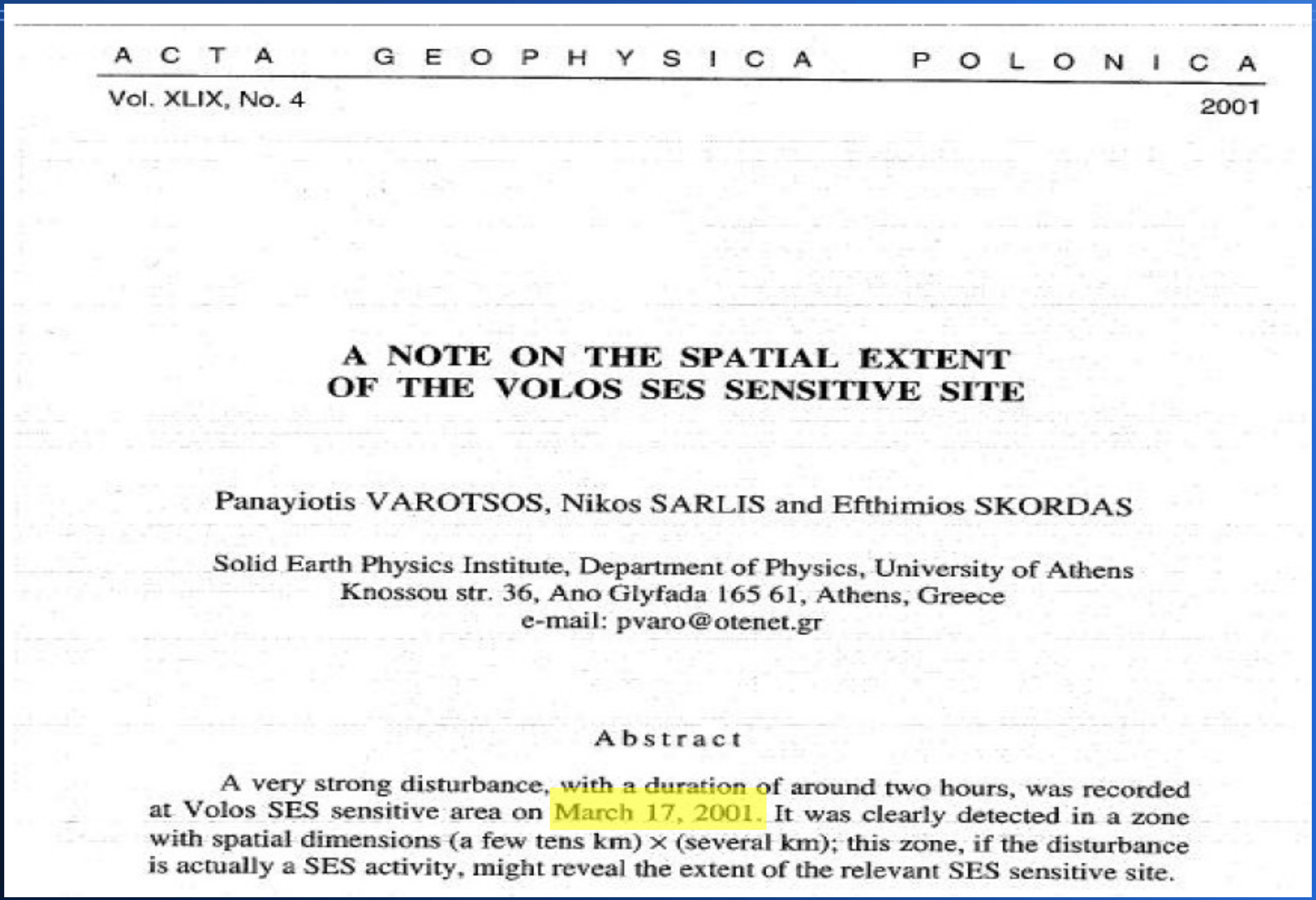
Signal	S	κ_1	S_-
K1	0.067±0.003*)	0.063±0.003*)	0.074±0.003
K2	0.081±0.003*)	0.078±0.004*)	0.103±0.003
E	0.071±0.010	0.071±0.006	0.082±0.010
A	0.070±0.008*)	0.068±0.004*)	0.084±0.008
U	0.092±0.004*)	0.071±0.004*)	0.071±0.004
T1	0.088±0.007	0.084±0.007	0.098±0.010
C1	0.083±0.004	0.074±0.002	0.080±0.004
P1	0.087±0.004	0.075±0.004	0.081±0.004
P2	0.088±0.003	0.071±0.005	0.072±0.015
E1	0.087±0.007	0.077±0.017	0.081±0.007
$M_1^{**)}$	0.094±0.005	0.075±0.004	0.078±0.003
$M_2^{**)}$	0.089±0.003	0.076±0.004	0.084±0.003
$M_3^{**)}$	0.089±0.004	0.080±0.005	0.093±0.004
$M_4^{**)}$	0.080±0.005	0.073±0.004	0.086±0.006
$V_1^{**)}$	0.078±0.006	0.074±0.004	0.092±0.005
$PAT^{***)}$	0.080±0.002	0.072±0.002	0.078±0.002
$PAT_2^{***)}$	0.074±0.002	0.075±0.002	0.078±0.002
$PIR_1^{****)}$	0.070±0.012	0.062±0.010	0.051±0.010
$PIR_2^{****)}$	0.077±0.004	0.076±0.005	0.082±0.004
$PAT_3^{****)}$	0.073±0.007	0.072±0.005	0.081±0.006
$PAT_4^{****)}$	0.085±0.005	0.073±0.007	0.080±0.004
PAT_5	0.067±0.007	0.074±0.007	0.079±0.007
PAT_6	0.071±0.005	0.069±0.003	0.066±0.005
PAT_7	0.072±0.003	0.067±0.003	0.069±0.003
PAT_8	0.070±0.005	0.065±0.005	0.070±0.005
PIR_3	0.086±0.003	0.070±0.005	0.070±0.005

man-made “artificial”

Table 4.6 Continued.

Signal	S	κ_1	S_-
n1	0.143±0.003*)	0.115±0.003*)	0.127±0.004
n2	0.103±0.003*)	0.093±0.003*)	0.122±0.003
n3	0.117±0.010*)	0.100±0.008*)	0.118±0.010
n4	0.106±0.010*)	0.100±0.013*)	0.138±0.010
n5	0.091±0.011*)	0.086±0.007*)	0.120±0.011
n6	0.102±0.007*)	0.084±0.004*)	0.095±0.007
n7	0.116±0.005	0.085±0.005	0.083±0.005
n8	0.117±0.004	0.095±0.007	0.099±0.005
n9	0.110±0.010	0.091±0.005	0.095±0.010
n10	0.112±0.005	0.087±0.007	0.087±0.006
n11	0.122±0.012	0.088±0.007	0.079±0.012
n12	0.104±0.005	0.094±0.005	0.103±0.009
n13	0.124±0.007	0.084±0.007	0.077±0.008
n14	0.124±0.005	0.087±0.005	0.081±0.007

The recording of SES activities are shown to be accompanied by characteristic changes of *independent geophysical data*



A C T A G E O P H Y S I C A P O L O N I C A

Vol. XLIX, No. 4 2001

A NOTE ON THE SPATIAL EXTENT OF THE VOLOS SES SENSITIVE SITE

Panayiotis VAROTSOS, Nikos SARLIS and Efthimios SKORDAS

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Abstract

A very strong disturbance, with a duration of around two hours, was recorded at Volos SES sensitive area on March 17, 2001. It was clearly detected in a zone with spatial dimensions (a few tens km) × (several km); this zone, if the disturbance is actually a SES activity, might reveal the extent of the relevant SES sensitive site.

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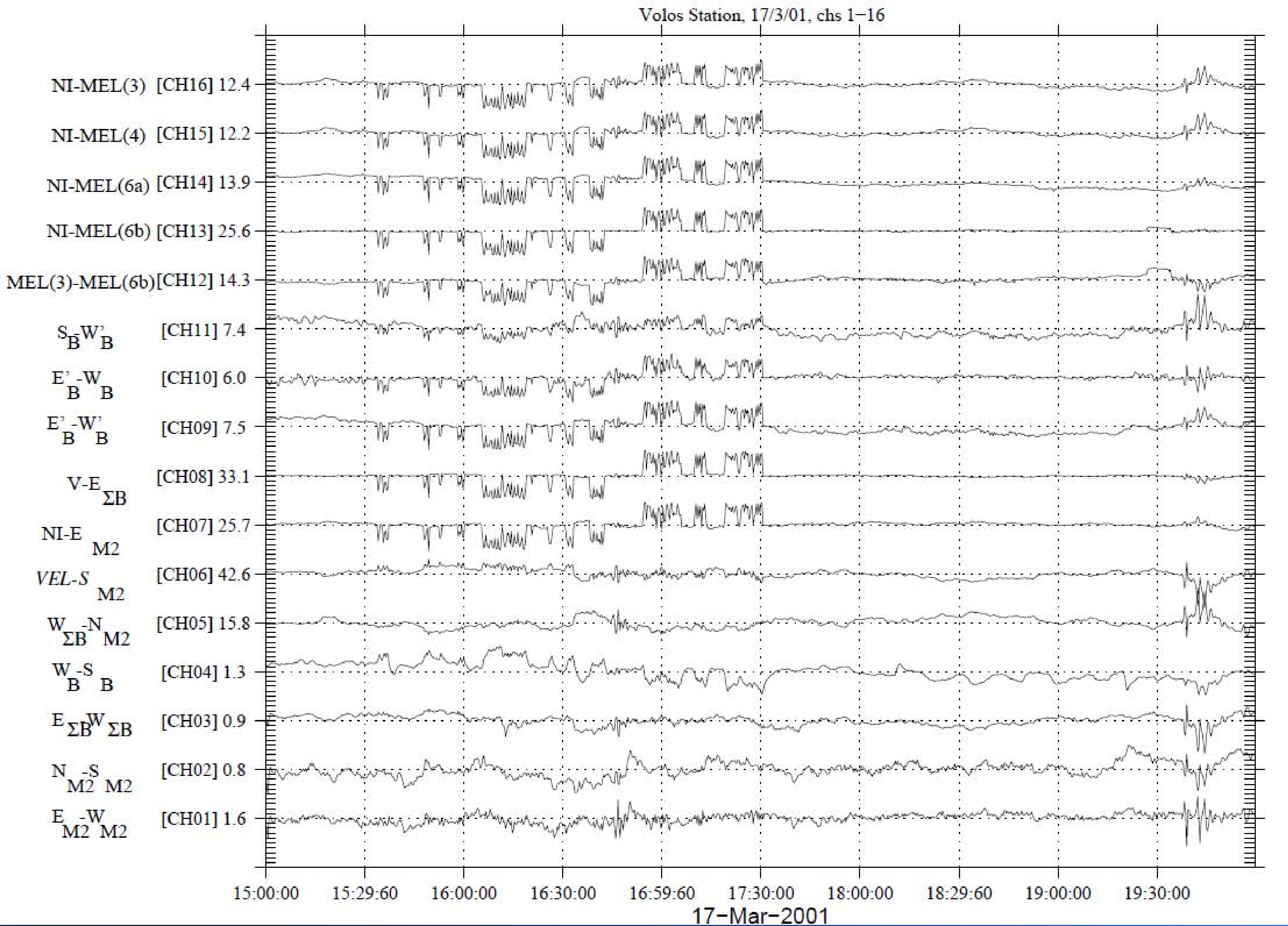
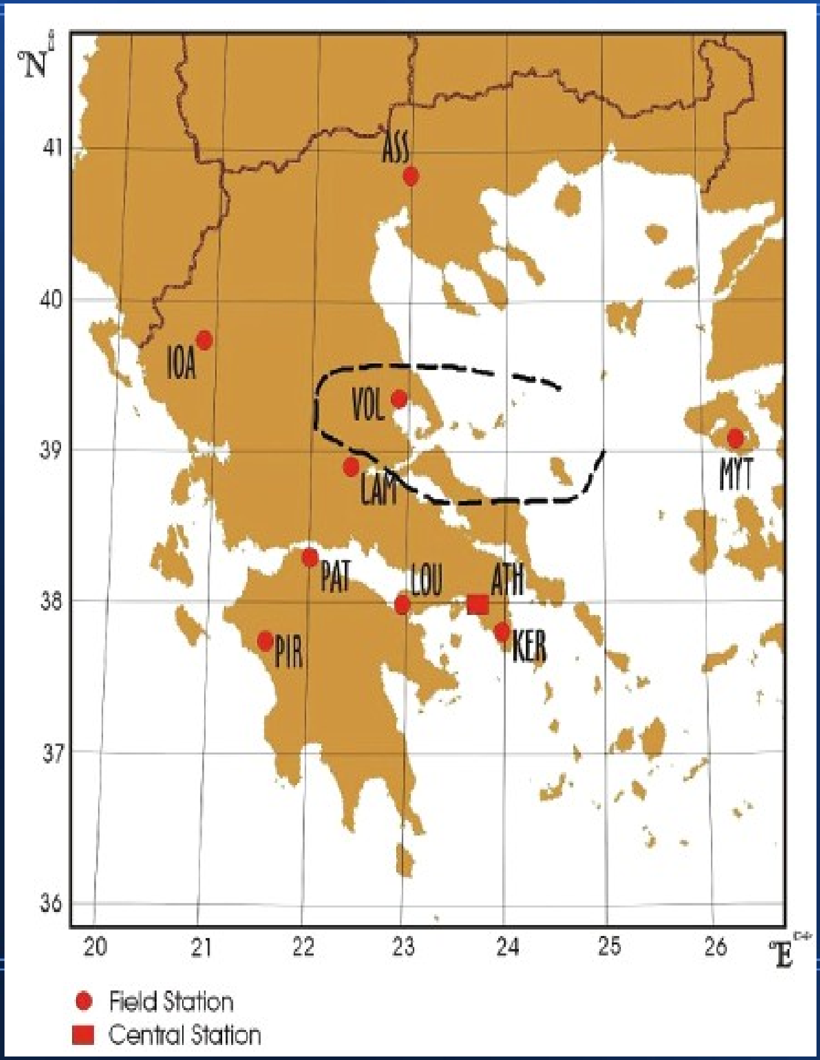
Appendix received on 29 July 2001
Accepted for publication on 6 August 2001



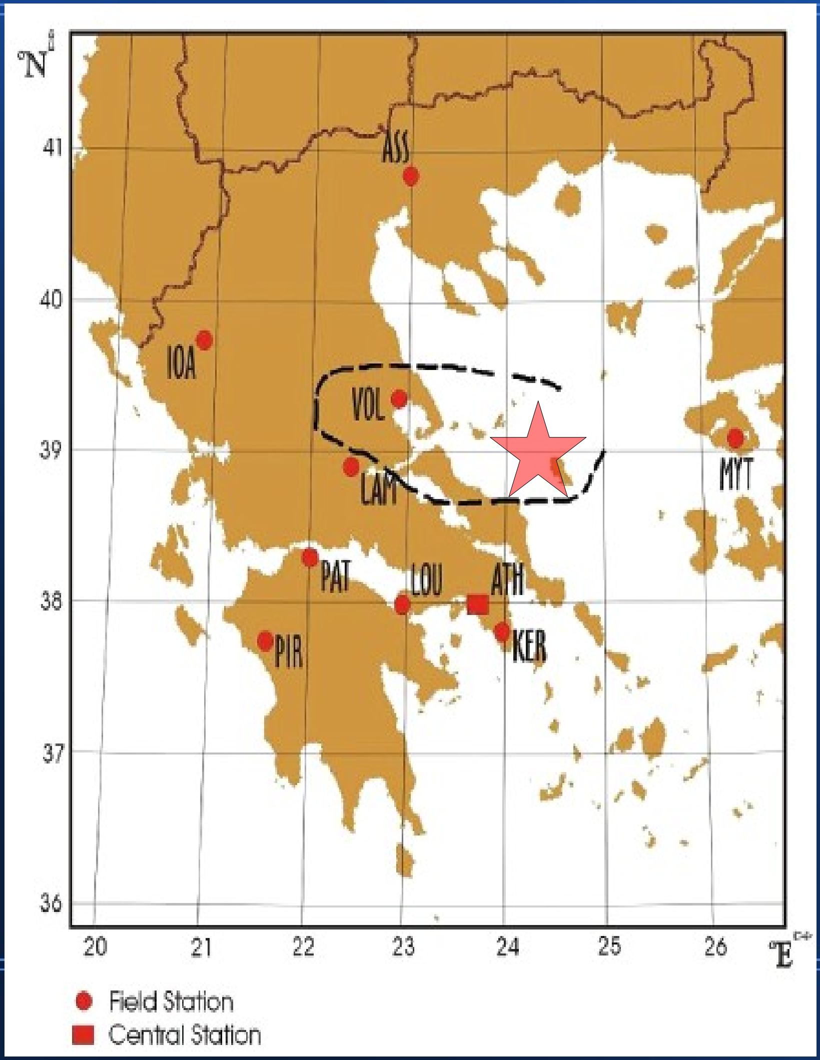
P. Varotsos, N. Sarlis, and E. Skordas, " A note on the spatial extent of the Volos SES sensitive site", *Acta Geophysica Polonica*, Vol. **49** (2001), 425-435.

The major Aegean Mw6.5 earthquake on July 26, 2001



The area ‘bordered’ by the broken curve (surrounding VOL) was the predicted area in Varotsos, P., Sarlis, N., Skordas, E.: *Acta Geophys. Pol.* **49**, 425–435 (2001) for the epicenter of the impending EQ related to the SES activity recorded at VOL (four months before).

The major Aegean Mw6.5 earthquake on July 26, 2001



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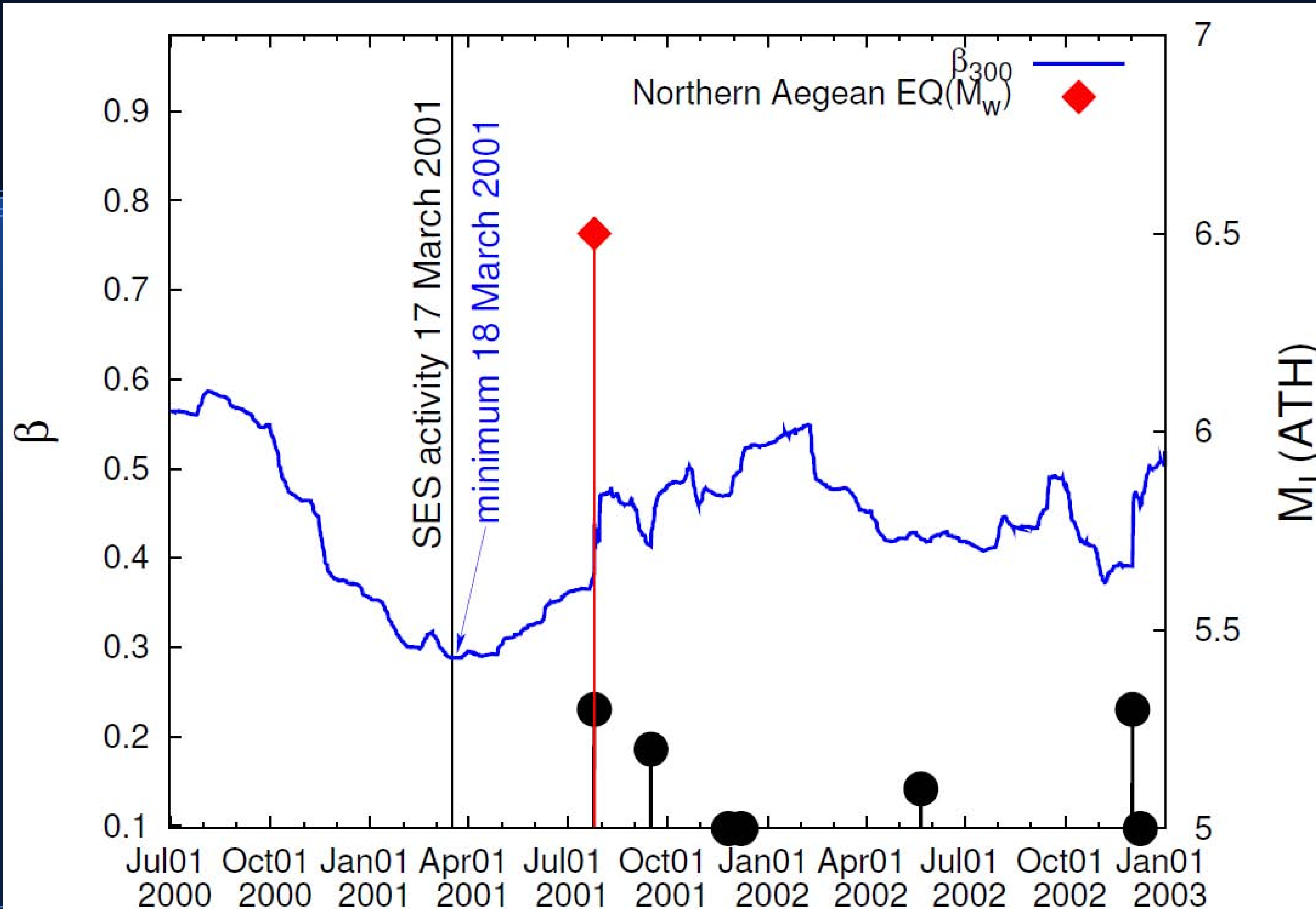

β_{300}
Northern Aegean EQ(M_w)
SES activity 17 March 2001
minimum 18 March 2001
β
M_L(ATH)
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
5
5.5
6
6.5
7
Jul01 2000
Oct01 2000
Jan01 2001
Apr01 2001
Jul01 2001
Oct01 2001
Jan01 2002
Apr01 2002
Jul01 2002
Oct01 2002
Jan01 2003

PHYSICAL REVIEW E **86**, 046107 (2012)

Earthquake networks based on similar activity patterns

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(Received 12 June 2012; published 15 October 2012)

Earthquakes are a complex spatiotemporal phenomenon, the underlying mechanism for which is still not fully understood despite decades of research and analysis. We propose and develop a network approach to earthquake events. In this network, a node represents a spatial location while a link between two nodes represents similar activity patterns in the two different locations. The strength of a link is proportional to the strength of the cross correlation in activities of two nodes joined by the link. We apply our network approach to a Japanese earthquake catalog spanning the 14-year period 1985–1998. We find strong links representing large correlations between patterns in locations separated by more than 1000 kilometers, corroborating prior observations that earthquake interactions have no characteristic length scale. We find network characteristics not attributable to chance alone, including a large number of network links, high node assortativity, and strong stability over time.

DOI: 10.1103/PhysRevE.86.046107 PACS number(s): 89.75.Da, 91.30.Px, 91.30.Ab, 91.30.Dk

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Seismic Electric Signals: An additional fact showing their physical interconnection with seismicity ☆

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A R T I C L E I N F O

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Criticality

A B S T R A C T

Natural time analysis reveals novel dynamical features hidden behind time series in complex systems. By applying it to the time series of earthquakes, we find that the order parameter of seismicity exhibits a unique change approximately at the date(s) at which Seismic Electric Signals (SES) activities have been reported to initiate. In particular, we show that the fluctuations of the order parameter of seismicity in Japan exhibits a clearly detectable minimum approximately at the time of the initiation of the SES activity observed by Uyeda and coworkers almost two months before the onset of the volcanic-seismic swarm activity in 2000 in the Izu Island region, Japan. To the best of our knowledge, this is the first time that, well before the occurrence of major earthquakes, anomalous changes are found to appear almost simultaneously in two independent datasets of different geophysical observables (geoelectrical measurements, seismicity). In addition, we show that these two phenomena are also linked closely in space.

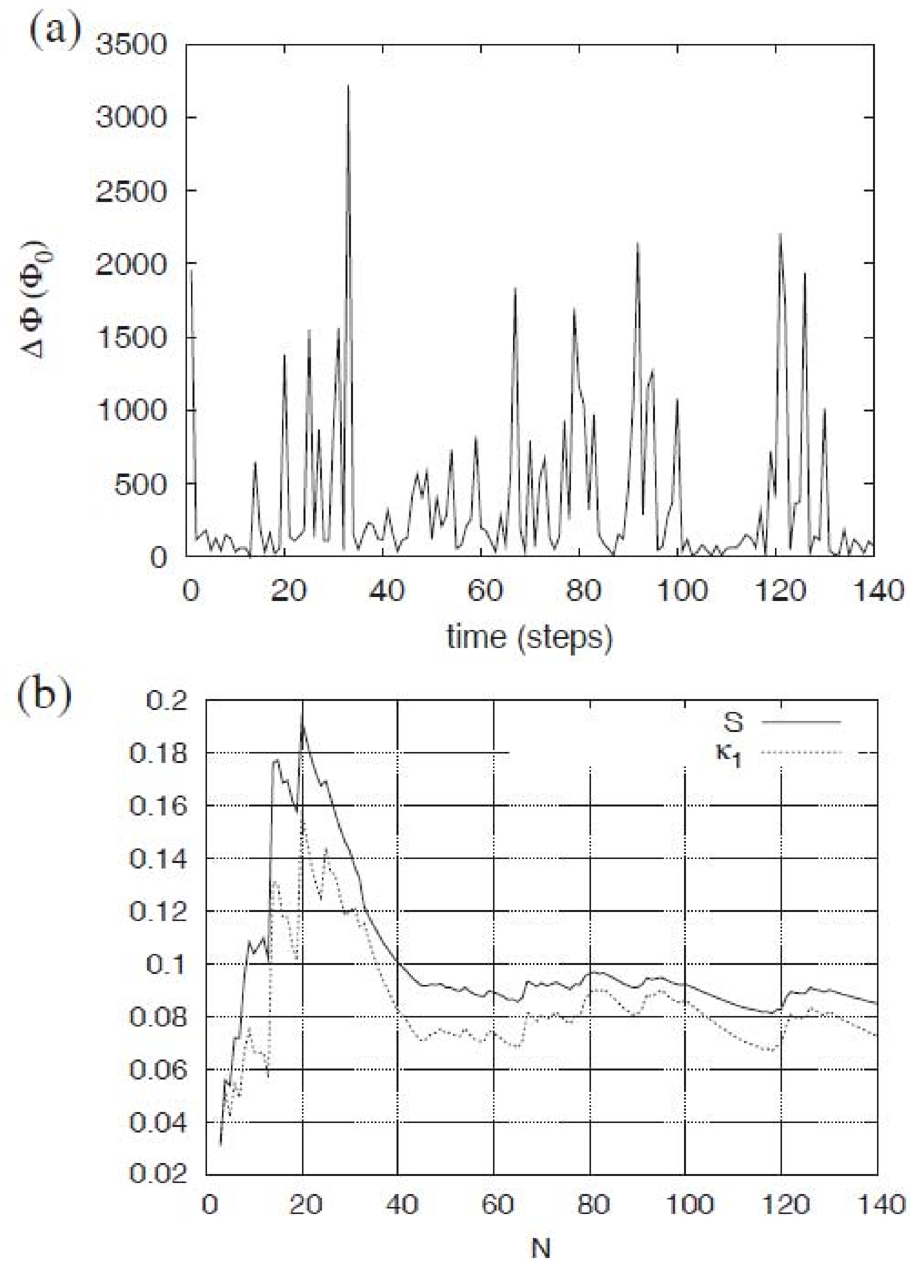


Fig. 8.19 (a): The time evolution of the magnetic flux in $YBa_2Cu_3O_{7-x}$ inside the sample over the 1st run of Fig.2 of Ref.[3]. (b): The results of the variance κ_1 (dotted) and the entropy S (solid) as they evolve event by event, when the data of (a) are analyzed in the natural time-domain. Taken from Ref.[70].

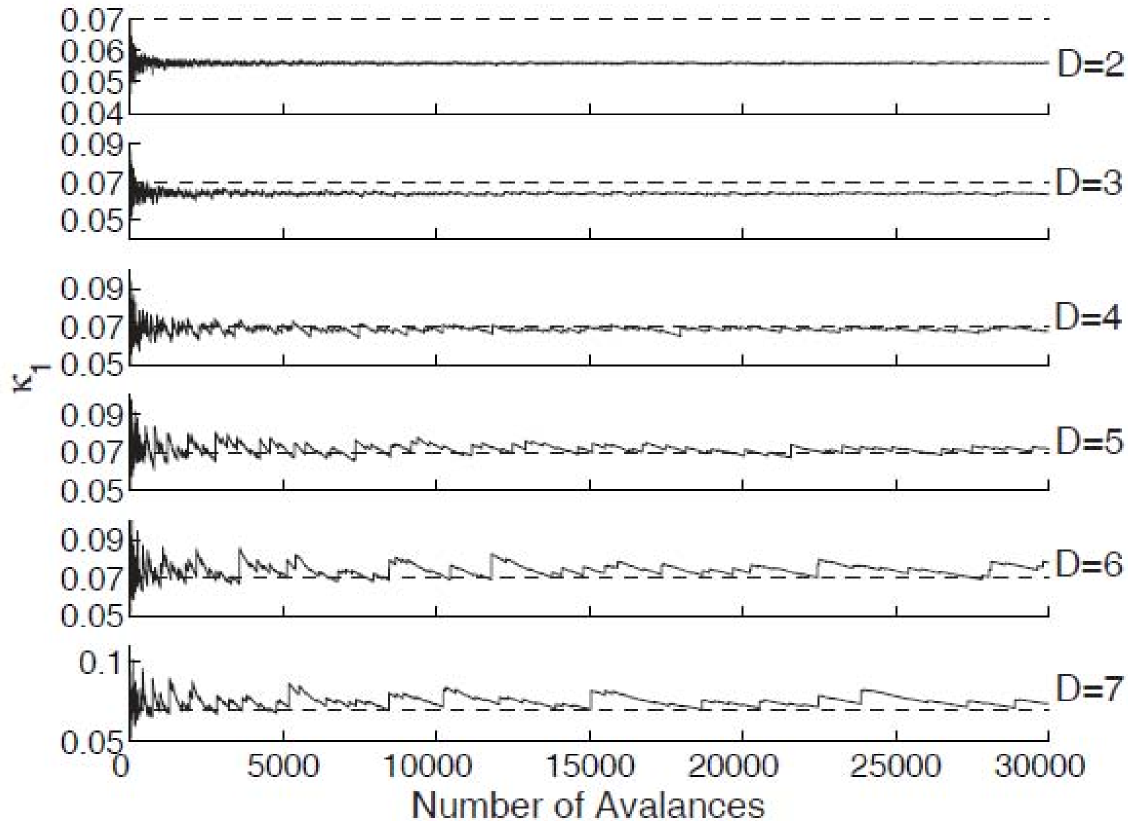


Fig. 8.16 The evolution of κ_1 values versus the number of consecutive avalanches for various D values, i.e., for **D=2** to **D=7**, for the centrally fed sandpile. The initial condition is $z_i = 0$. For the sake of comparison, the broken horizontal line shows the value of $\kappa_1 = 0.070$. Taken from Ref.[81].

Heartbeats warn of sudden death risk

DUNCAN GRAHAM-ROWE

HOW do you tell a healthy heart from one that could stop without warning? By measuring variations in the length of the heartbeat, according to a team of researchers in Greece.

The finding could provide a way to screen for people at risk of sudden cardiac death. Such people's heartbeat often looks perfectly healthy by conventional criteria. Yet a quarter of a million people die each year in the US alone when their heart suddenly stops and, like the soccer player Marc-Vivien Foé who collapsed and died last year while playing for Cameroon, many of them have had no history of heart problems.

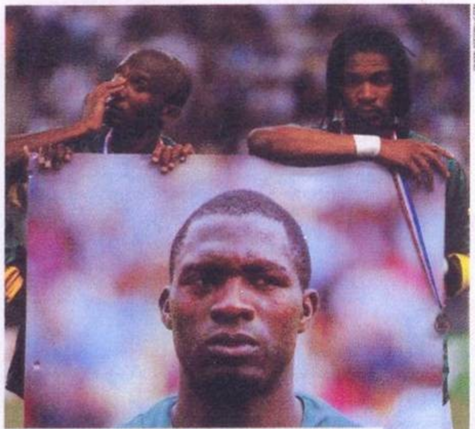
Even a person's ECG, or electrocardiogram, can look normal for much of the time. In patients with Brugada syndrome, for example, abnormal electrical signals sporadically stop their hearts from pumping properly. Long QT syndrome is a similar condition, which can strike young, fit adults, and has also been linked to cot death.

Standard approaches to analysing ECGs tend to focus on the peaks and troughs of the trace. Instead, Panayiotis Varotsos of the University of Athens has been studying the variation in the length of time it takes for the heart to complete one beat (see Graphic, below).

The amount of variation in the rate of heartbeats is already used to measure aerobic fitness, with more variation meaning a fitter heart. However, for Varotsos the crucial test is the variation in the length of each beat, and whether this variation is random. He adapted equations he had previously used to describe physical systems such as earthquakes to predict that, in a healthy heart, these variations will have some degree of order. But if there is something wrong with the heart, however subtle, it should disrupt that order, making the variation more random.

To test the theory, Varotsos and his colleagues analysed 95 sample ECGs taken from public databases of people with various heart conditions and 10 from healthy patients. He found that the beats of the diseased hearts did indeed vary more randomly and the results are to be published in a future issue of *Physical Review E*.

"The method could be particularly useful for screening those who have a family history of sudden cardiac death"



Footballer Marc-Vivien Foé died of a cardiac arrest on the pitch last year

Varotsos says the method could be used as an initial screen to flag up all types of heart problems. "In principle our method should be applied to all causes of cardiac arrest."

A lot of research has gone into discovering ways to identify cardiac diseases from an ECG. Some have used data mining techniques – screening blind for any effect that comes up, while other studies have looked for chaotic signatures that might distinguish unhealthy hearts from healthy ones (*New Scientist*, 3 January 1998, p 20).

But so far no method has stood up to scrutiny in clinical trials, says Arun Holden, a computational biologist at the University of Leeds, UK. Varotsos believes his discovery has a better chance of turning out to be real because he used a physical model of how the heart works to predict a specific effect.

However, as Tim Bowker of the British Heart Foundation points out, there is no way of knowing more about the patients whose ECGs were used in the database. "Without knowing this, one doesn't know that it applies to any group other than these 105," he says. So the jury will remain out until the method is tested to see if it is able to predict cardiac health.

If it proves reliable, the method could be particularly useful for screening those who have a family history of sudden cardiac death. In the UK, about 3500 people die from this syndrome each year. This may not be enough to give rise to a nationwide screening programme.

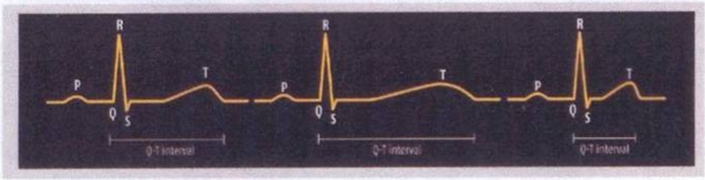
Instead, Varotsos suggests that cardiologists could apply his method to Holter monitors – the portable ECG devices that are used to monitor patients thought to be at risk. ●

HEART ATTACK WARNING?

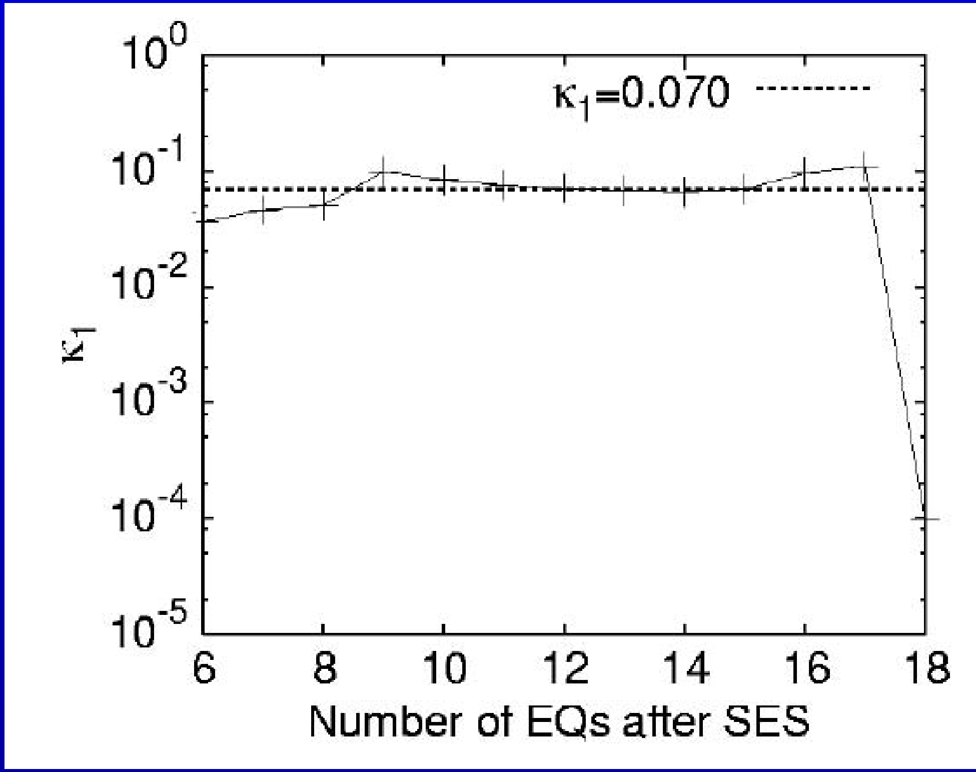
Varotsos and colleagues studied ECG traces and found that the more random the variation in Q-T interval, the higher the risk of sudden cardiac death

P – Atrial depolarisation: top chambers contract QRS – Ventricular depolarisation: larger, lower chambers contract

ST – Ventricular repolarisation: cells in the lower chambers recharge, in preparation for the next contraction



Why κ_1 behaves like an OP for EQs?

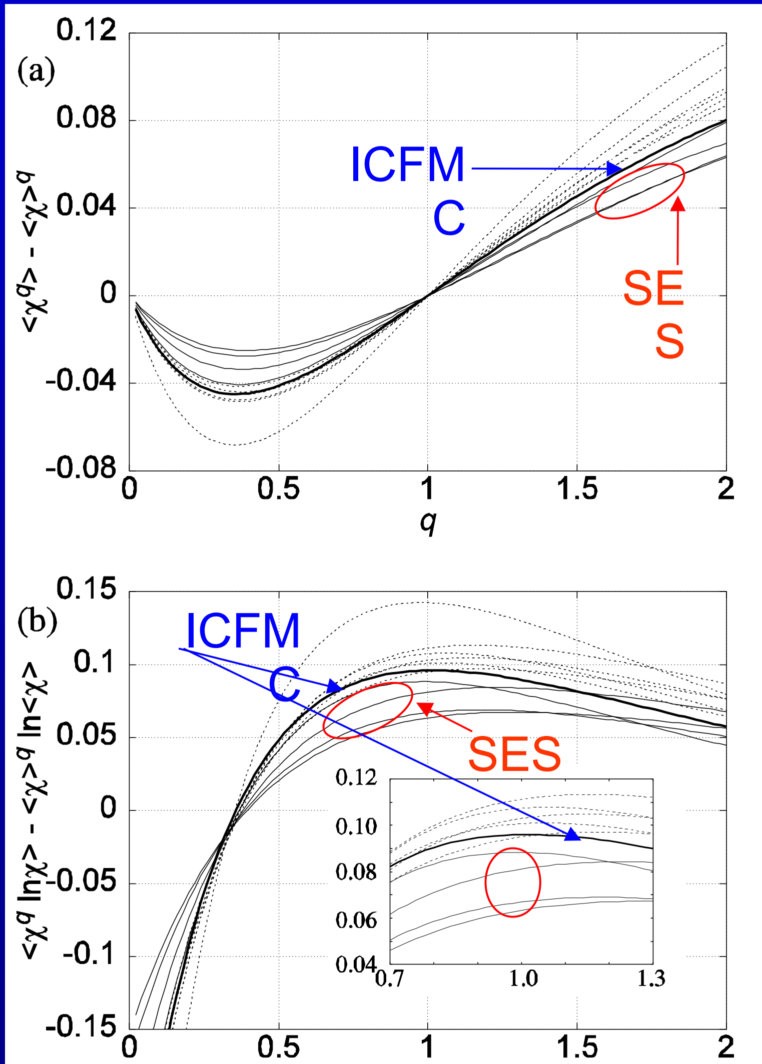


The value of κ_1 after the Seismic Electric Signal on April 18, 1995 until the 6.6 Kozani-Grevana EQ on May 13, 1995 (labelled 18).

- κ_1 is non-zero before the occurence of a strong earthquake (EQ) (like magnetization M is non-zero below the Curie temperature in the unsymmetrical phase)
- κ_1 becomes zero upon the occurrence of a strong EQ (like M is zero above the Curie temperature in the symmetrical phase)

Varotsos P. A., Sarlis N. V., Tanaka H. K. and Skordas E. S., Phys. Rev. E, 72 (2005) 041103.

What happens with the q-th order fluctuation functions $\Delta(q)=\langle\chi^q\rangle - \langle\chi\rangle^q$?



- We observe that $\Delta(q)$ pass through 0 when q=1 since $\Delta(q=1)=0$.
- As said $\Delta(q=2)\equiv\kappa_1$ (=0.070 for critical systems).
- We observe that the curvature in the region [1,2] is not high. Thus, the distinction of critical from non-critical systems may probably stem from the value of derivative of $\Delta(q)$ *for q*=1. *Thus, the derivative*

$$\Delta'(q)=\langle\chi^q \ln\chi\rangle - \langle\chi\rangle^q \ln\langle\chi\rangle$$

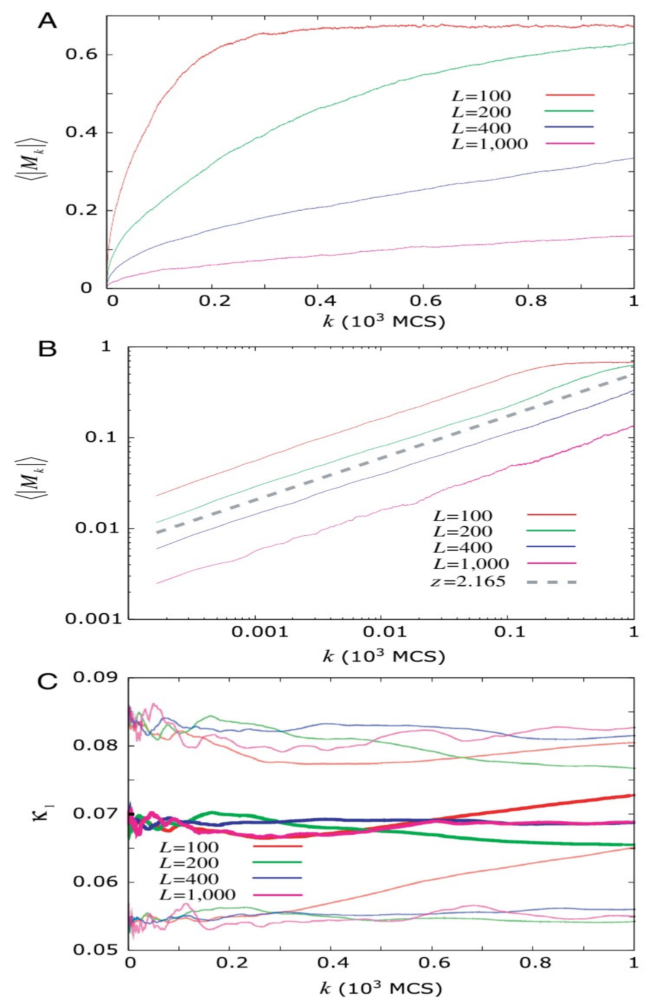
for q=1 of the q-th order fluctuation function may be of primary importance in Natural Time Analysis

Varotsos et al., Practica of Athens Academy ***76****, 294* (2001);*Phys. Rev. E.* **68**, 031106 (2003)

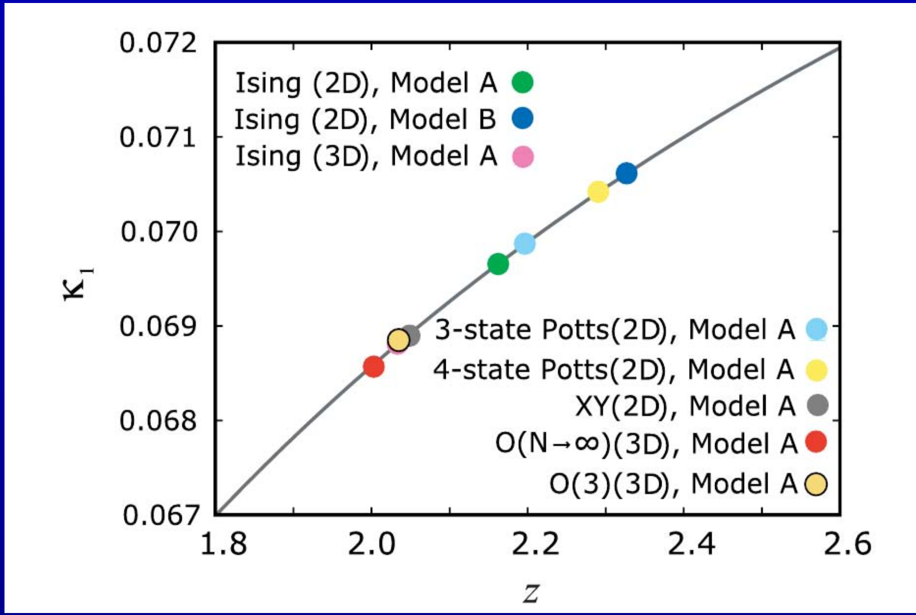
Why κ$_1$ =0.07 for critical systems?

Having in mind that p(χ)~ξ, and ξ~t$^{1/z}$ as the system approaches criticality, we make the ansatz

$$p(\chi)=N_c\chi^{1/z}$$



$$\kappa_1=\frac{1+z}{1+3z}-\left(\frac{1+z}{1+2z}\right)^2.$$



P. Varotsos, N. V. Sarlis, E. S. Skordas, S. Uyeda, and M. Kamogawa,Proc. Natl. Acad. Sci. U.S.A. 108, 11361 (2011).

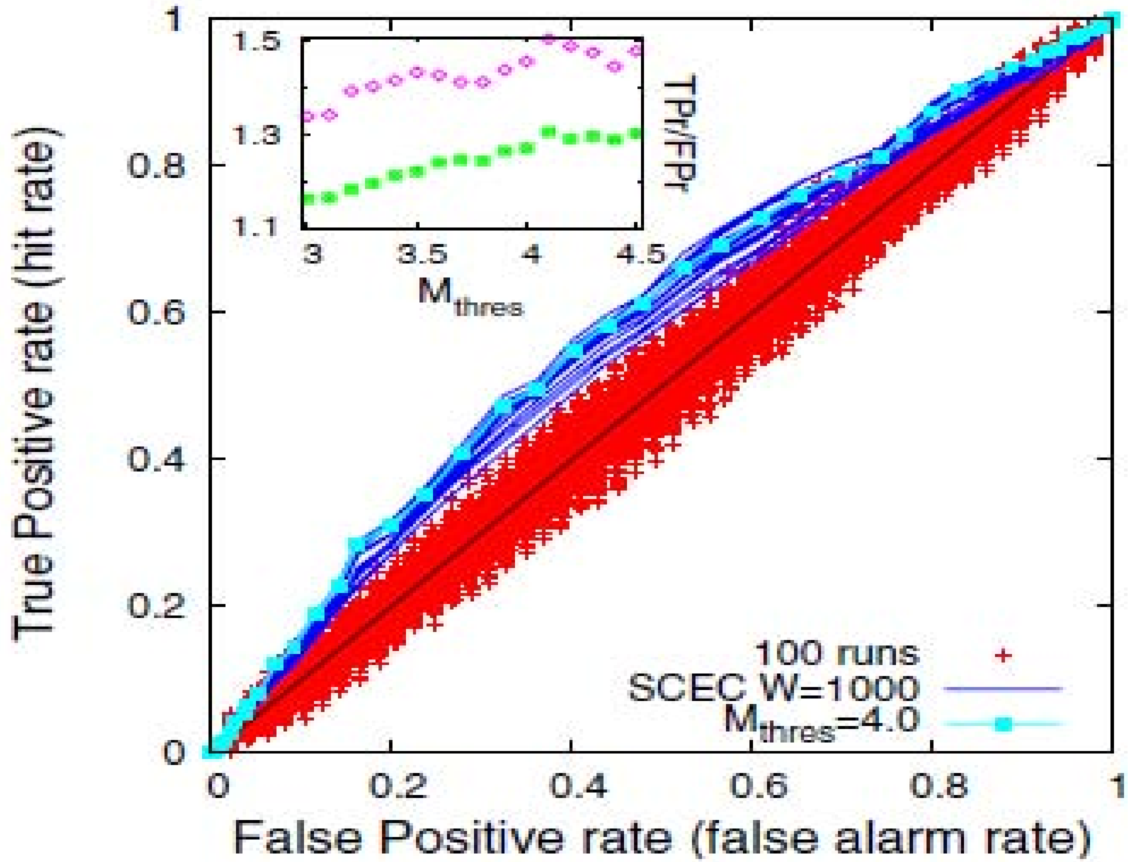


Fig. 5: (Color online) The ROC curves constructed using $\beta_k(W)$ for $W = 1000$ as decision variable (the case of $M_{thres} = 4$ is shown in light blue color as a guide) together with 10^2 repetitions of the prediction scheme using a uniformly distributed random number as decision variable (see the text).The inset depicts the ratio of the true positive rate (TPr) over the false positive rate (FPr) *vs.* M_{thres}, for FPr $\approx 25\%$ (magenta diamonds) and FPr $\approx 50\%$ (green stars).