Article

Estimating the Epicenter of an Impending Strong Earthquake by Combining the Seismicity Order Parameter Variability Analysis with Earthquake Networks and Nowcasting: Application in the Eastern Mediterranean

Panayiotis K. Varotsos ¹ , Jennifer Perez-Oregon ^{2,3} , Efthimios S. Skordas ^{3,4} and Nicholas V. Sarlis ^{3,4,*}

¹ Section of Geophysics and Geothermy, Department of Geology and Geoenvironment, National and Kapodistrian University of Athens, Panepistimiopolis Zografos, 157 84 Athens, Greece; panvar@noa.gr

² Departamento de Física, Escuela Superior de Física y Matemáticas, Instituto Politécnico Nacional, UP Zacatenco C.P., Mexico City 07738, Mexico; jnnfr.po@gmail.com

³ Solid Earth Physics Institute, Department of Physics, National and Kapodistrian University of Athens, Panepistimiopolis Zografos, 157 84 Athens, Greece; eskordas@phys.uoa.gr

⁴ Section of Condensed Matter Physics and Solid Earth Physics Institute, Department of Physics, National and Kapodistrian University of Athens, Panepistimiopolis Zografos, 157 84 Athens, Greece

* Correspondence: nsarlis@phys.uoa.gr; Tel.: +30-210-727-6736

Citation: Varotsos, P.K.; Perez-Oregon, J.; Skordas, E.S.; Sarlis, N.V. Estimating the Epicenter of an Impending Strong Earthquake by Combining the Seismicity Order Parameter Variability Analysis with Earthquake Networks and Nowcasting: Application in the Eastern Mediterranean. *Appl. Sci.* **2021**, *11*, 10093. <https://doi.org/10.3390/app112110093>

Academic Editor: Marco Vona

Received: 15 September 2021

Accepted: 22 October 2021

Published: 28 October 2021

Publisher's Note: MDPI stays neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Copyright: © 2021 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

Abstract: The variance κ_1 of the natural time analysis of earthquake catalogs was proposed in 2005 as an order parameter for seismicity, whose fluctuations proved, in 2011, to be minimized a few months before the strongest mainshock when studying the earthquakes in a given area. After the introduction of earthquake networks based on similar activity patterns, in 2012, the study of their higher order cores revealed, in 2019, the selection of appropriate areas in which the precursory minima β_{min} of the fluctuations β of the seismicity order parameter κ_1 could be observed up to six months before all strong earthquakes above a certain threshold. The eastern Mediterranean region was studied in 2019, where all earthquakes of magnitude $M \geq 7.1$ were found to be preceded by β_{min} without any false alarm. Combining these results with the method of nowcasting earthquakes, introduced in 2016, for seismic risk estimation, here, we show that the epicenter of an impending strong earthquake can be estimated. This is achieved by employing—at the time of observing the β_{min} —nowcasting earthquakes in a square lattice grid in the study area and by averaging, self-consistently, the results obtained for the earthquake potential score. This is understood in the following context: the minimum β_{min} is ascertained to almost coincide with the onset of Seismic Electric Signals activity, which is accompanied by the development of long range correlations between earthquake magnitudes in the area that is a candidate for a mainshock.

Keywords: earthquake physics; earthquake networks; natural time analysis; order parameter fluctuations; earthquake nowcasting; eastern Mediterranean

1. Introduction

The natural time analysis (NTA) was introduced in the early 2000s [1–3], and revealed hidden properties in the time series of complex systems that cannot be observed in conventional time; for a review, see, e.g., [4]. It has found applications in various disciplines ranging from statistical physics [5–8], solid state physics [9] and, rock physics [10] to environmental physics [11–13], cardiology [14–18], and engineering [19–21]. The NTA has also found various applications in the context of seismology and physics of earthquakes (EQs); see, e.g., [3,22–45]. Such an application is presented in this paper.

The EQs exhibit power law correlations in time, space, and magnitude (M) [46–69] that have been suggested [70,71] to indicate the proximity to a critical point [72–76]. Several proposals suggest [73,74,77] that the EQ dynamics are associated with a second-order

phase transition, or with a mean-field spinodal [76] that can be understood as a line of critical points. A first-order phase transition (see, e.g., [78] and references therein) has also been proposed as an alternative. In phase transitions, the new phase corresponds to the mainshock and a quantity-termed order parameter is required to correctly identify the new phase. Landau and Lifshitz [79] state: “To describe quantitatively the change in the structure of the body when it passes through the phase transition point, we can define a quantity η , called the order parameter, in such a way that it takes non-zero (positive or negative) values in the unsymmetrical phase and is zero in the symmetrical phase”.

Along these lines, Varotsos et al. [23] proposed the variance κ_1 of the NTA of EQ catalogs as an order parameter for seismicity. As such, it is non-zero before the mainshock, falling abruptly to zero upon its occurrence (see, e.g., the last points in Figure 6 by Márquez et al. [80]) and its scaled distribution exhibits a behavior similar to that of other equilibrium and non-equilibrium critical systems [7,21,23,28,81]. Later, it was shown that, when studying the EQs in a given area, the fluctuations β of this order parameter were minimized a few months before the strongest mainshock [82], and the experimental results revealed that such minima occurred almost simultaneously with the observation of Seismic Electric Signals (SES) activities [83], which are series of low frequency ($f \leq 1$ Hz) electric signals that precede strong EQs [84–90]. Subsequent studies have shown that such minima are observed before strong EQs, both regionally [29] and globally [91]. These minima were found to be statistically significant precursors of EQs [92–94]. Furthermore, Varotsos et al. [95] showed that regional β_{min} in Japan is observed when long-range correlations develop between EQ magnitudes, which has also been verified in two recent strong EQs in the Americas [40,96].

In recent decades, the theory of networks [97–101] has triggered many applications in seismicity (see, e.g., [47,60,102–108]), which showed that the EQ network properties may reveal a seismic hazard [109–114]. Tenenbaum et al. [60] introduced the EQ networks based on similar activity patterns (ENBOSAP) which are very useful for the NTA of seismicity [83]. Furthermore, the study of the higher order cores of these networks allowed the selection of appropriate areas in which the precursory minima β_{min} of the fluctuations of the seismicity order parameter κ_1 can be observed up to six months before all strong mainshocks above a certain threshold [115]. In particular, the case studied in 2019 was the eastern Mediterranean region and resulted in five precursory β_{min} before all EQs of magnitude $M \geq 7.1$ without false alarms.

It is the scope of the present paper to show that by combining the above two NTA results with the modern method of nowcasting EQs [33], an estimate of the epicenter of the impending EQ with $M \geq 7.1$ in the eastern Mediterranean region is achieved. EQ nowcasting employs natural time, which is unique in its characteristics [116], to estimate seismic risk by means of an EQ potential score (EPS) and found many useful applications, both regionally and globally [33,116–126]. EQ nowcasting [33] has, so far, focused on describing the current state of fault systems.

2. Materials and Methods

2.1. Study Area and EQ Data

Here, the area of interest was the eastern Mediterranean, see Figure 1. We used the United States National Earthquake Information Center (NEIC) PDE catalog—the data available from the United States Geological Survey (USGS), cf. [127]—in the region $N_{23}^{52}E_{50}^{50}$, and considered all EQs recorded during the period of almost 45 years from November 1976 to February 2021 with $M_{thres} = 3.8$. The eastern Mediterranean Sea and its surrounding coastal areas of Greece and western Turkey are one of the most seismically active and rapidly deformed regions on the continents [128]. This area is tectonically dominated by the relative plate motions between Eurasia and African lithosphere plates and their microplates. The African plate moves north to Eurasia from Gibraltar to the east. The plate boundary crosses North Africa and continues into southern Sicily, continuing around the Adriatic through Italy and eastern Balkans to Albania and northwestern Greece. There is a suggestion that the Adriatic is part of the African plate forming a small plate called

Apulia [129]. The Apulia plate has a continental structure, e.g., it has a similar mean density to the density of the Eurasian plate, and their interaction leads to a continental collision. This microplate is suggested to rotate counter clockwise and its interaction with Eurasia is responsible for the shallow EQs in the region of Croatia, Albania and northwestern Greece. East of Apulia, the rapid movement of two small plates, the Aegean and the Turkish, takes up the relative movement between the Eurasia and African plates. The Aegean plate consists of the Aegean Sea, part of the Greek peninsula, Crete, and part of the western area of Asia Minor, while the Turkish part includes most of Asia Minor and Cyprus. The collision between Arabia and Eurasia in the Caucasus and eastern Turkey forces the Turkish plate to move westward in relation to Eurasia. Due to this movement, the strain accumulates along the North Anatolian transform fault (e.g., the opposite sides of this fault belong to different plates that move horizontally on top of each other) that accommodates large destructive EQs. The northern front of the African plate, south of the Adriatic Sea, forms the eastern Mediterranean oceanic lithosphere. As this oceanic lithosphere has a higher density than the continental lithosphere of the Aegean plate, it sinks below it, with an average angle of 38° , and forms the Hellenic Arc (SW of Cefallonia to S. Peloponnese, S. Crete up to S. Rhodes) and is associated with a sharp crustal shortening and an uplift rate of a few mm/yr along the Hellenic Arc due to the accretion of sediments of the African plate below the overriding Aegean plate [130]. Most of the subduction movement is accommodated along the Hellenic arc causing shallow depth EQs at its outer part. The seismically active regions of western Turkey, eastern and northern Greece, and the northern Aegean Sea are dominated by extension forces such as the southern Aegean Sea move in an almost southwesterly direction relative to Eurasia. This extension is thought to be driven principally by the “roll-back” of the subducting slab below the southern Aegean, as it sinks into the mantle [131]. The geophysical properties are different in the Aegean Sea from those in the outer part of the Hellenic arc. Another geotectonic feature causing destructive EQs is the significant right-lateral strike-slip movement along the North Aegean trough, and the Cephalonia–Lefkada transform zone, which is due to the offset between the oceanic–continental convergence to the west and the westward propagation of the Anatolian plate to the east. The combination of all the above factors leads to a significant left-lateral movement along the southeastern front of the Aegean–African interface [130].

Figure 1. Map of the area $N_{23}^{52}E_5^{50}$ together with the plate boundaries (blue) according to Bird [132]. The epicenters of the strong EQs with $M \geq 7.1$ since 1981 are shown with cyan diamonds. The EQs from top to bottom are: the 1986 M7.2 Vrancea

EQ, the 1999 M7.6 Izmit and M7.2 Düzce EQs, the 1981 M7.2 Lesvos EQ, the 2011 M7.1 Van EQ, the 1990 M7.4 Manjil-Rudbar EQ, the 2017 M7.3 Halabja EQ, and the 1995 M7.2 Aqaba EQ. The 6-core of the ENBOSAP of the region $N_{25}^{50}E_5^{46}$ is depicted with the (red) links and nodes. The red rectangle shows the geographical area (A_6) that marginally encloses this 6-core, i.e., $N_{28}^{50}E_7^{44}$. We note that the corresponding 5-core, hereafter labeled A_5 , covers the whole region $N_{25}^{50}E_5^{46}$ and is bounded by the green rectangle.

2.2. Minima of the Variability of the Order Parameter of Seismicity

In a time series comprising N EQs, the natural time χ_k for the occurrence of the k -th EQ of energy Q_k is defined as $\chi_k = k/N$. This means that the time intervals between consecutive events are ignored, but their order, as well as their energy, Q_k are preserved. In NTA, the evolution of the pair (χ_k, p_k) is studied, where:

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

is the normalized energy and Q_k is estimated by means of the relation [133] $Q_k \propto 10^{1.5M_k}$, where M_k stands for the EQ magnitude. It has been argued [23], as mentioned in the Introduction, that the variance $\kappa_1 = \langle \chi^2 \rangle - \langle \chi \rangle^2$ of natural time χ weighted for p_k , namely:

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

can be considered as an order parameter for seismicity. The study of the fluctuations of this order parameter of seismicity in an EQ catalog was conducted through a fixed-length sliding natural time window containing a number W of consecutive EQs that would occur on average within the crucial scale [82] of a few months, or so, which is the average lead time of SES activities. Following the procedure described by [29,95], we estimated κ_1 from the subexcerpts of consecutive 6 to W EQs within the window of W EQs and, then, calculated the average value $\mu_W(\kappa_1)$ and the standard deviation $\sigma_W(\kappa_1)$ of the obtained κ_1 values. The quantity:

$$\beta_W \equiv \frac{\sigma_W(\kappa_1)}{\mu_W(\kappa_1)} \quad (3)$$

was termed [4,134] variability of κ_1 . The temporal evolution of the β_W value (Figure 2) could then be pursued by sliding the natural time window of W consecutive EQs, event by event, through the EQ catalog and assign to its value, the occurrence time of the EQ which follows the last EQ of the window in the EQ catalog. The corresponding minimum value was labeled $\beta_{W,min}$. The quantity β_W of Equation (3) is reminiscent [115] of the square root of the Ginzburg criterion introduced in the context of the mean field theories of phase transitions of the Ginzburg–Landau type (see, e.g., p. 175 of Goldenfeld [135]). The latter criterion was also discussed by Holliday et al. [72].

To identify a precursory variability minimum [29,91,95], two window lengths, W and W' ($W' > W$), corresponding to the number of EQs that occurred within a few months, were selected and β_W and $\beta_{W'}$ (sliding independently event by event) should have exhibited their local minima almost simultaneously. This meant that one required at least 90% of the EQs included in the calculation of the local β_W minimum, and were also included in the calculation of the local $\beta_{W'}$ minimum. Once this condition was valid, it was examined whether the ratio $r \equiv \beta_{W',min} / \beta_{W,min}$ laid within the margins defined by the precursory to strong EQ variability minima; see, e.g., [29,91,95]. For example, for the area A_6 of Figure 1, the selection of $r \in (r_1 = 0.98, r_2 = 1.07)$ led to 7 variability minima (see Table 2 of [115]) when imposing a threshold $\beta_0 = 0.253$ below which the minima of β_W for $W = 80$ must be considered by the aforementioned procedure (cf. $W = 80$ EQs corresponds to the number of EQs occurring on average in area A_6 of Figure 1 within two months).

Figure 2. Results for the variabilities β_W when $W = 80$ and 120 consecutive EQs of the seismicity order parameter κ_1 in natural time for the almost 40-year study period within the marginal geographical areas A_6 and A_5 that enclose the 6-core and the 5-core of the ENBOSAP of the region $N_{25}^{50}E_5^{46}$, respectively. The magnitude of EQs (right scale) is depicted by the (black) vertical lines ending in solid circles for EQs that occur within the A_6 . When the vertical line does not end in a solid circle, the EQ occurs inside the A_5 , but outside the A_6 , i.e., the 2017 M7.3 Halabja EQ. The (red) open circles indicate the uniquely identified minima β_{120} [115] when comparing the β_W values for both areas A_6 and A_5 . They precede all the mainshocks of $M \geq 7.1$ within A_6 by six months at the most, without false alarms, see the red rectangle of Figure 1. The horizontal line at 0.253 was designed as an eye guide.

2.3. Earthquake Networks Based on Similar Activity Patterns

Tenenbaum et al. [60] suggested the construction of the ENBOSAP as follows: The area under study was evenly spaced in geographical coordinates in “squares” of dimensions of about $100 \text{ km} \times 100 \text{ km}$, each marked by two integers (i, j) . The center of each “square” is a possible node of the network. The fact that EQs do not occur on a daily basis in every square makes it necessary to coarse-grain the seismic activity over a predefined time interval. There is a trade-off between precision and data richness leading [60] to an optimal coarseness in the 90-day time series. Thus, the seismic activity s_t in each square covered 90 days and s_{t+1} corresponded to the next 90 days of non-intersecting time periods, giving about 4 different values per year. The energy released in each 90-day period inside the “square” with indices (i, j) was given by [60]:

$$s_t(i, j) \equiv \sum_{l=1}^{N_t(i, j)} 10^3 M_t^l(i, j), \quad (4)$$

where $N_t(i, j)$ is the number of EQs displayed in the 90-day t -th time window with epicenter inside the square (i, j) of magnitude $M_t^l(i, j)$ above a given threshold M_{thres} , i.e., $M_t^l(i, j) \geq M_{thres}$. To define a link between the centers of two squares, say (i, j) and (i', j') , one calculated the Pearson product-moment correlation $r_{x, y}$ between the time series $x_t \equiv s_t(i, j)$ and $y_t \equiv s_t(i', j')$:

$$r_{x,y} \equiv \frac{\langle xy \rangle - \langle x \rangle \langle y \rangle}{\sigma_x \sigma_y}, \quad (5)$$

where $\langle \dots \rangle$ indicates the average value of $\dots$, and σ_x and σ_y are the standard deviations of x_t and y_t , respectively. The two grid squares were linked if $r_{x,y}$ was greater than a specified value r_c , which is a tunable parameter. Mintzelas and Sarlis [115] found that, for NTA applications of ENBOSAP, r_c should be chosen as the one that determines the upper 5% percentile of the positive $r_{x,y}$ among all the different squares; for the eastern Mediterranean region, the value $r_c = 0.7$ was selected. As usual, the degree k of a node was the number of links the node had. Tenenbaum et al. [60] showed that ENBOSAP: (a) displays links without a characteristic length scale with much more links than expected only by chance alone, (b) is much more assortative than random ones, and (c) exhibits significant stability over time. These findings corroborated the existence of high-degree nodes with similar activity patterns over a distance of more than 1000 km away; see, for example, Figure 1.

2.4. Earthquake Nowcasting

Rundle et al. [33] proposed EQ nowcasting as a method for estimating the current state of fault systems in the sense that it determines the progress in the EQ cycle. To achieve this determination, one uses an EQ catalog to calculate from the ‘small’ EQs, which are defined as those with magnitude $M < M_\lambda$, but above a threshold M_σ , i.e., of magnitude $M \in [M_\sigma, M_\lambda)$, the level of hazard for ‘large’ $M \geq M_\lambda$ EQs. The lower threshold M_σ is typically the completeness threshold of the EQ catalog used [33], while the EQ catalogs employed [33,116,117,123,124,136] are global seismic catalogs such as the Advanced National Seismic System Composite Catalog or the NEIC PDE catalog. For such global catalogs, a $M_\sigma = 4.0$ magnitude threshold was considered [116,117] for applications in EQ-prone areas outside the United States, such as those in Greece, Japan, and India. By employing the natural time concept, one counts the number n of small EQs that occur after a large EQ. In other words, n is the waiting (natural) time or interoccurrence natural time. The current number $n(t)$ of small EQs, since the occurrence of the last strong EQ, is compared to the cumulative distribution function (CDF) of the interoccurrence natural time $Prob[n < n(t)]$. For such an estimate of $Prob[n < n(t)]$, it should have been ensured [33] that we had enough data to span at least 20 or more strong EQ cycles. In EQ nowcasting, the EQ potential score (EPS) equals the CDF value,

$$EPS = Prob[n < n(t)], \quad (6)$$

and is a measure of the level of current hazard, see Figure 3a. In References [33,116,117,123,136], the seismic risk for various cities of the world was estimated through the following procedure: After calculating the CDF $Prob[n < n(t)]$ within a large area, the number $\tilde{n}$ of the small EQs around a city, i.e., those occurring within a circular region of epicentral distances $r < R$ since the occurrence of the last strong EQ in this circular region, was found. Given that EQs exhibit ergodicity—see, e.g., References [58,137,138]—Rundle et al. [117] suggested that the seismic risk around a city can be estimated by using the EPS corresponding to the current value of $\tilde{n}$ by inserting $n(t) = \tilde{n}$ in Equation (6).

In the present study, the large area considered was $N_{23}^{52}E_5^{50}$ which, for $M_\sigma = 4.0$ and $M_\lambda = 6.0$, led to the CDF shown in Figure 3a. A study of the empirical CDF comprising 123 EQ cycles in Figure 3a revealed that the fit with the Weibull distribution provided a good approximation with a root mean square of residuals equal to 0.0207; see Chapter 15 of [139]. This property of the Weibull distribution was in accordance with the results found by Pasari and Sharma [123] for Himalayan EQs.

Figure 3. (a) The cumulative distribution of the number n of EQs with $M \geq 4.0$ that occurred between two EQs of magnitude $M \geq 6.0$ in the area $N_{23}^{52}E_5^{50}$ of Figure 1. The results came from 123 EQ cycles after using the Weibull model; see Table 1 of [123]. (b) The mean value and the standard deviation of the EPS estimated at the nearest to the epicenter point of a $0.1^\circ \times 0.1^\circ$ square degrees grid at the time of the minima are depicted by the (red) open circles in Figure 2 as a function of the coarse grain radius R . The (black) thick straight lines were designed as a guide for the eye.

3. Results

The importance of high-degree nodes of ENBOSAP in the NTA of seismicity was first suggested in Reference [83]. It was observed that the inclusion of high-degree nodes in the geographical area in which we applied the NTA of seismicity was important for the clearer observation of $\beta_{W,min}$ before strong EQs. In order to determine the important high-degree nodes that should have been included in the geographical areas where we studied seismicity in natural time, Mintzelas and Sarlis [115] searched for k -cores in ENBOSAP. Recall that a k -core in a network is the largest subgraph whose vertices have a degree at least k [99]. Thus, in a k -core, each node has at least k nearest neighbors within that subgraph; see, e.g., the six-core depicted in red color in Figure 1. It is noteworthy that a network is hierarchically organized as a set of successfully enclosed k -cores [99], similar to the Russian nesting doll “Matrioshka”. In other words, the five-core covered an area larger than the six-core and, as a network, it included the six-core itself; see Figure 1b,c of Reference [115]. The NTA of seismicity improved when we comparatively examined [115] the results from the areas $N_{25}^{50}E_5^{46}$ (labeled A_5) and $N_{28}^{50}E_7^{44}$ (labeled A_6) of the five-core and the six-core of the area $N_{25}^{50}E_5^{46}$, respectively, in a fashion similar to that followed in [95]. More precisely, when focusing on the minima $\beta_{W,min}$, which were simultaneously observed in both areas A_5 and A_6 , we found that they preceded within six months, without any false alarm, all strong EQs with $M \geq 7.1$ in the smaller region, i.e., A_6 (see the red rectangle in Figure 1). The results for the variabilities β_W for both areas A_5 and A_6 for $W = 80$ and 120 EQs, corresponding to the number of EQs that occurred on average there for the periods of (approximately) two and three months, respectively, are shown in Figure 2 for the almost forty-year period from 1 January 1981 to 9 February 2021. A careful inspection of this figure showed that no additional minima were observed simultaneously since October 2018, which was the end of the period studied by [115]. In the same figure, with (red) open circles we marked the simultaneous $\beta_{120,min}$ that preceded the strong EQs with $M \geq 7.1$ in area A_6 , as mentioned. The dates corresponding to these minima are given in Table 1. In the same Table, we also inserted the date of another local minimum in both areas A_5 and A_6 which did not meet the criteria, $\beta_{80} < \beta_0 = 0.253$ and $r_1 < r < r_2$, mentioned in the Materials and Methods to be considered as precursory, but it could be useful to provide an estimate of the epicenter of the Düzce EQ.

Table 1. The dates of the five almost simultaneously (within 3 months) observed minima in the limiting geographical areas A_5 and A_6 of the 5-core and the 6-core of the area $N_{25}^{50}E_5^{46}$, respectively, together with the strong EQs that they had preceded. ^a They are marked with (red) open circles in Figure 2. In the last line, a local minimum that was also observed before Düzce EQ was also added; see Figure 2.

$\beta_{W,min}$ Date	EQ Date	M	Epicenter Location
10 July 1981	19 December 1981	7.2	Lesvos, Greece
7 March 1986	30 August 1986	7.2	Vrancea, Romania
24 August 1995	22 November 1995	7.2	Aqaba, Jordan
6 April 1999	17 August 1999	7.6	Izmit, Turkey
4 October 2011	23 October 2011	7.1	Van, Turkey
8 September 1999	12 November 1999	7.2	Düzce, Turkey

^a These data came from a compilation of Tables 2 and 3 of [115].

Since the aforementioned minima provided an estimate of the occurrence time (i.e., within the subsequent six months) of the $M \geq 7.1$ EQs without any false alarm, we now proceeded to an estimate of the epicenter location of the impending EQ. The NTA already provided an answer to this question [31,32] based on the simultaneous observation of β minima calculated in the large area and in various small areas. The latter was found to cluster around the epicenter location of the impending EQ. Such a method, however, required detailed seismological catalogs for a large geographical region such as those provided by the Japan Meteorological Agency. Unfortunately, in the case of the eastern Mediterranean region studied here, such a catalog does not yet exist and, hence, this method could not be applied at present. To partially overcome this lack, we employed the following procedure: We applied the EQ nowcasting to circular areas of radius R with centers located at the points of a grid of $0.25^\circ \times 0.25^\circ$ and estimated for each center an EPS value based on the Weibull approximation of the CDF depicted in Figure 3a. A self-consistent way to obtain an estimate of the epicenter location of the impending EQ would then be to average the aforementioned calculated EPS values within a circular area of radius R around the point P and assign this average EPS, $\langle \text{EPS} \rangle$, to it. In this way, we could obtain for $R = 250$ km the $\langle \text{EPS} \rangle$ maps shown in Figure 4, which were calculated at the date of the minimum $\beta_{W,min}$ (see the first column of Table 1) preceding the $M \geq 7.1$ EQs whose epicenters were depicted by the (black) open squares. Comparing the $\langle \text{EPS} \rangle$ maps with these epicenters, we saw a reasonable agreement.

A model to understand the process of self-consistently averaging EPS is shown in Figure 5; to keep this model simple, we assumed that all EQs occurred practically in the center O of the yellow-colored circular region “Y” of radius R . After a long enough period without a large EQ, the EPS took the value of unity for all points inside “Y” and, since we assumed that no other EQ took place, the EPS would be zero outside it. Hence, the value of $\langle \text{EPS} \rangle$ at a point P lying at a distance d away from O simplified to:

$$\langle \text{EPS} \rangle = \frac{A(d, R)}{\pi R^2}, \quad (7)$$

where $A(d, R)$ is the (red) line-shaded area of the two intersecting circles shown in Figure 5, and equaled [140]:

$$A(d, R) = 2R^2 \arccos\left(\frac{d}{2R}\right) - d\sqrt{R^2 - \left(\frac{d}{2}\right)^2}. \quad (8)$$

Hence, the value of $\langle \text{EPS} \rangle$ in polar coordinates (ρ, θ) with center at O equaled to:

$$f(\rho) = \frac{2}{\pi} \arccos\left(\frac{\rho}{2R}\right) - \frac{\rho}{\pi R} \sqrt{1 - \left(\frac{\rho}{2R}\right)^2} \quad (9)$$

for $\rho < 2R$ and zero otherwise. If we now calculate the mean value of $\langle \text{EPS} \rangle$:

$$m(R, R') = \frac{\int_0^{R'} \int_0^{2\pi} f(\rho) \rho d\theta d\rho}{\pi R'^2} = \frac{2 \int_0^{R'} f(\rho) \rho d\rho}{R'^2} \quad (10)$$

in a circular region of radius $R' > 2R$, we simply obtain that:

$$m(R, R') = \left(\frac{R}{R'}\right)^2 \quad (11)$$

by virtue of the integrals $\int_0^{2R} \arccos\left(\frac{\rho}{2R}\right) \rho d\rho = \pi R^2/2$ and $\int_0^{2R} \rho^2 \sqrt{1 - \left(\frac{\rho}{2R}\right)^2} d\rho = \pi R^3/2$. The validity of Equation (11) was verified by assuming that EQs occurred according to the aforementioned simple model and, using the computer programs used for the calculation of the $\langle \text{EPS} \rangle$ maps shown in Figure 4, the numerically found $m_n(R, R')$ had the form:

Figure 4. Maps of the area $N_{25}^{50}E_{10}^{50}$ together with the plate boundaries (blue) according to [132] depicting by color scale the $\langle \text{EPS} \rangle$ for $R = 250$ km at the time of the observation of β_{min} [115], see the (red) open circles of Figure 2, before all the mainshocks of $M \geq 7.1$ within the area A_6 , see the red rectangle of Figure 1. The EQ epicenters are shown by the (black) open squares in each case. For the 1999 M7.2 Düzce EQ, the local β_{120} minimum observed on 8 September 1999 (see Figure 2) was used. The latter minimum was not as deep as those identified in Reference [115]; see the discussion there about Düzce EQ, which was followed by the deadly 7 September 1999 M6.0 Athens EQ and was discussed later here.

$$m_n(R, R') = \left(\frac{R}{R'} \right)^{d_f} \quad (12)$$

with $d_f = 1.986(5)$, which was very close to two, and $R' = 1961(14)$ km, which was also very close to the radius (1913 km) of an area corresponding to the approximately 11.5×10^6 km² covered by the area $N_{23}^{53}E_{10}^{50}$ used for the construction of the $\langle \text{EPS} \rangle$ maps. Additionally, when the quantity $m_n(R, R')$ was studied for the $\langle \text{EPS} \rangle$ maps of Figure 4, the corresponding quantities were $d_f = 1.32(6)$ and $R' = 1320(80)$ km. Interestingly, this value of d_f differed only slightly from the value $d_f \approx 1.2$, which Bak et al. [46] found to describe the fractal dimension of the location of epicenters projected onto the surface of the Earth in a unified scaling law obeyed by the distribution of waiting times between EQs occurring in California and ranging from tens of seconds to tens of years.

Figure 5. The value of EPS was considered unity inside the yellow-colored circular region of radius R with center at O —this disk was called region “Y” in the text—and zero outside. The $\langle \text{EPS} \rangle$ was calculated for a point P lying at distance d from the center of the yellow-colored region and equals to the ratio of the (red) line-shaded region over the area πR^2 of the circle having its center at P .

4. Discussion

An inspection of Figure 4 revealed that the epicenters of the impending EQs correlated favorably with the $\langle \text{EPS} \rangle$ maps. Of course, $M \geq 7.1$ EQs did not occur in areas where $\langle \text{EPS} \rangle$ was highest, but rather in regions where $\langle \text{EPS} \rangle$ was rather mediocre. Detailed results showed that the $\langle \text{EPS} \rangle$ values at the grid points nearest to the epicenters laid in the range from 19% to 50%. Namely, this $\langle \text{EPS} \rangle$ value equaled 22% for Lesvos EQ, 28% for Vrancea EQ, 21% for Aqaba EQ, 19% for Izmit EQ, 30% for Düzce EQ, and 50% for Van EQ. This result was probably related to the fact that, at the time of $\beta_{W,min}$, long-range correlations started to develop in the magnitude time series [40,95,141].

Interestingly, the above results were consistent with respect to the two free parameters of the proposed method (i.e., the grid size and the radius R) were concerned. If we considered the five EQs with $M \geq 7.1$ for which simultaneous minima were identified at the same time (i.e., see the first five rows of Table 1) and studied the statistics of $\langle \text{EPS} \rangle$ of the closest to the epicenters grid points versus R , we found that their mean exhibited a plateau centered at $R \approx 250$ km, which was also accompanied by an inflection point for the corresponding standard deviation (STD); cf. Figure 3b. This result was obtained for a $0.1^\circ \times 0.1^\circ$ grid and a similar behavior was found for the $0.25^\circ \times 0.25^\circ$ grid used for drawing the maps of Figure 4. Indeed, the selection of $R = 250$ km in the latter figure was determined on this basis. Note that $R = 250$ km was also used in the NTA of seismicity of Japan [31] for estimating the epicenter of an impending $M \geq 7.6$ EQ. At this point, it should be noted that when using the empirical CDF shown in Figure 3a instead of its Weibull approximation, the results did not change significantly and the maps remained almost the same.

In view of the aforementioned ability of the $\langle \text{EPS} \rangle$ maps calculated at the time of $\beta_{W,min}$ to provide information on the impending EQ epicenter for $M \geq 7.1$, we proceeded

to the calculation of such maps upon the occurrence of $\beta_{W,min}$ that, although were not simultaneous in areas A_5 and A_6 , were followed by an EQ of $M \in [6.5, 7.0]$ within six (or at the most seven) months. The dates of such minima are listed in the first column of Table 2, and were used for the construction of the $\langle \text{EPS} \rangle$ maps shown in Figure 6. Figure 6 was drawn by using a $0.25^\circ \times 0.25^\circ$ grid as in Figure 4. In the last column of Table 2, the $\langle \text{EPS} \rangle$ estimated at the grid points nearest to the impending EQ epicenter are shown (cf. they had an average value 38% and an STD of 20%). A similar calculation revealed an average of 38% and an STD of 18% when a grid $0.1^\circ \times 0.1^\circ$ was used, pointing to the stability of the calculation.

Table 2. The dates of minima observed in the limiting geographical areas of either the 5-core or the 6-core of the area $N_{25}^{50}E_5^{46}$ that preceded the EQs with $M \geq 6.5$, but were not simultaneous in both areas. ^a On the last row, a local minimum that was also observed before the deadly Athens EQ was also added, see Figure 2. In the last column, we also inserted the $\langle \text{EPS} \rangle$ value at the grid point nearest to the epicenter when a $0.25^\circ \times 0.25^\circ$ grid was used as in Figure 6.

$\beta_{W,min}$ Date	EQ Date	M	Epicenter Location	$\langle \text{EPS} \rangle$ (%)
22 June 1982	17 January 1983	7.0	Kefalonia, Greece	64
21 June 1983	6 August 1983	6.8	Lemnos, Greece	32
3 April 1990	30 May 1990	7.0	Vrancea, Romania	20
11 November 1990	29 April 1991	7.0	Racha, Georgia	21
9 April 2001	26 July 2001	6.5	Skyros, Greece	36
21 January 2002	3 February 2002	6.5	Afyon, Turkey	10
15 April 2015	17 November 2015	6.5	Lefkada, Greece	55
12 June 2017	12 November 2017	7.3	Halabja, Iraq	31
24 April 2018	25 October 2018	6.8	Zakynthos, Greece	71
3 September 1999	7 September 1999	6.0	Athens, Greece	53

^a These data came from a compilation of Tables 2 and 3 of [115].

Of course, the present method is a long way from becoming a really practical one, and we are still in the progress of improving it, since the cover of areas in Figures 4 and 6 was too large to find the final epicenter of an impending strong EQ. It provides, however, insight to the very difficult question of forecasting strong EQs. At this point, it is worthwhile to add that, in the case of Japan, where better quality seismological data exist, we could obtain a better estimation of a future EQ epicenter location by means of an NTA [31,32].

The two cases of the local minima during September 1999, which corresponded to the last row of Table 1 and the last row of Table 2, concerning Düzce and Athens EQs, respectively, were of particular regional interest. These two minima were not reported before, as they corresponded to values β_{80} and β_{120} , which were both well above 0.253. Their existence as local minima could be verified in Figure 2, while the corresponding $\langle \text{EPS} \rangle$ maps shown in Figures 4 and 6 correlate well with the epicenters of the deadly EQs of Düzce and Athens in 1999. Interestingly, the minimum of β_{80} on 3 September 1999 roughly coincided with the observation of an SES activity near Lamia, Greece, which was related to the deadly Athens EQ; see Chapter 17 of Lazaridou-Varotsos [142] (see also p. 105 of Reference [90]).

Moreover, a close inspection of Figure 2 revealed that local minima of β_{80} in area A_6 coincided with the SES activities recorded on 17 March 2001 [143], 7 November 2007 [144], and 2 October 2018 [136]. These results were remarkable, as they provided additional evidence to support the conclusion [83] that SES activities were accompanied by clear variations of seismicity, giving rise to simultaneous precursory phenomena in independent geophysical observables. This behavior was, of course, more obvious in the case of mega-EQs such as the 2011 M9.0 Tohoku EQ in Japan. In particular, it was found that the deepest minimum β_{min} of the order parameter κ_1 of seismicity during the 27-year period from 1 January 1984 to the occurrence of the 2011 Tohoku EQ occurrence on 11 March 2011 was observed on 5 January 2011 [29], which agreed with the experimental finding that β_{min} was observed [83] when an SES activity was initiated. This was so because the date of 5 January 2011 overlapped with the

observation [145–147] of the abnormal magnetic field variations on the z-component from 4 to 10 January 2011 at two measuring sites—see Figure 1 of [148]—laying at epicentral distances of around 130 km, a fact which was characteristic of the existence of an SES activity [4].

Figure 6. Same as Figure 4, but here, the $\langle \text{EPS} \rangle$ was calculated at the time of the β_{120} minimum reported in Tables 2 and 3 of [115] for all ‘false alarms’ preceding the strong $M \geq 6.5$ EQs within the area A_5 . The EPS evaluated (at the time of the local minimum of β_{80}) on 3 September 1999 before the deadly M6.0 Athens EQ is also shown; see Figure 2. Note that, although a strong EQ activity was evolving at Izmit at that time, a strong EQ struck the Greek capital.

5. Conclusions

Here, we showed that upon computing maps of the average earthquake potential score in a self-consistent manner, we could obtain information on the epicenter location of an impending strong EQ. This was achieved by employing earthquake nowcasting at the time of the observation of the minimum β_{min} of the fluctuations of the order parameter of seismicity. Such a minimum almost coincided with the SES activities, which were characterized by the development of long-range correlations, and became more easily detectable when a natural time analysis was employed in the areas covered by the higher order cores of the EQ networks based on similar activity patterns.

Author Contributions: Conceptualization, P.K.V., J.P.-O., E.S.S. and N.V.S.; methodology, P.K.V., J.P.-O., E.S.S. and N.V.S.; software, P.K.V., J.P.-O. and N.V.S.; validation, P.K.V., J.P.-O. and E.S.S.; formal analysis, P.K.V., E.S.S. and N.V.S.; investigation, P.K.V. and N.V.S.; resources, J.P.-O., E.S.S. and N.V.S.; data curation, E.S.S. and N.V.S.; writing—original draft preparation, P.K.V., E.S.S. and N.V.S.; writing—review and editing, P.K.V., J.P.-O., E.S.S. and N.V.S.; visualization, P.K.V. and N.V.S.; supervision, E.S.S. and N.V.S.; project administration, N.V.S.; funding acquisition, J.P.-O. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: Earthquake data came from the United States National Earthquake Information Center PDE and were downloaded from the United States Geological Survey, Earthquake Hazards Program [127]. The last date the data were accessed was 9 February 2021. Gnuplot [149] was used for the preparation of the figures. The coast lines were imported from GEODAS Coastline Extractor [150]. The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

Acknowledgments: Jennifer Perez-Oregon deeply appreciates the support from the National Council of Science and Technology (CONACYT) of Mexico (CVU No. 376516).

Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

The following abbreviations are used in this manuscript:

A_5	5-core limiting area of ENBOSAP
A_6	6-core limiting area of ENBOSAP
CDF	Cumulative distribution function
ENBOSAP	Earthquake networks based on similar activity patterns
EPS	Earthquake potential score
EQ	Earthquake
M	Magnitude
NE	Northeast
NEIC	National earthquake information center
NTA	Natural time analysis
PDE	Preliminary determination of epicenters
S	South
SES	Seismic electric signals
STD	Standard deviation
SW	Southwest
USGS	United States geological survey

References

1. Varotsos, P.A.; Sarlis, N.V.; Skordas, E.S. Spatio-Temporal complexity aspects on the interrelation between Seismic Electric Signals and Seismicity. *Pract. Athens Acad.* **2001**, *76*, 294–321.
2. Varotsos, P.A.; Sarlis, N.V.; Skordas, E.S. Long-range correlations in the electric signals that precede rupture. *Phys. Rev. E* **2002**, *66*, 011902. [[CrossRef](#)] [[PubMed](#)]
3. Varotsos, P.A.; Sarlis, N.V.; Skordas, E.S. Seismic Electric Signals and Seismicity: On a tentative interrelation between their spectral content. *Acta Geophys. Pol.* **2002**, *50*, 337–354.

4. Varotsos, P.A.; Sarlis, N.V.; Skordas, E.S. *Natural Time Analysis: The New View of Time. Precursory Seismic Electric Signals, Earthquakes and Other Complex Time-Series*; Springer: Berlin/Heidelberg, Germany, 2011. [\[CrossRef\]](#)
5. Varotsos, P.A.; Sarlis, N.V.; Skordas, E.S. Long-range correlations in the electric signals the precede rupture: Further investigations. *Phys. Rev. E* **2003**, *67*, 021109. [\[CrossRef\]](#)
6. Varotsos, P.A.; Sarlis, N.V.; Skordas, E.S.; Uyeda, S.; Kamogawa, M. Natural time analysis of critical phenomena. *Proc. Natl. Acad. Sci. USA* **2011**, *108*, 11361–11364. [\[CrossRef\]](#)
7. Sarlis, N.V.; Skordas, E.S.; Varotsos, P.A. Similarity of fluctuations in systems exhibiting Self-Organized Criticality. *EPL (Europhys. Lett.)* **2011**, *96*, 28006. [\[CrossRef\]](#)
8. Sarlis, N.V.; Skordas, E.S.; Varotsos, P.A. The change of the entropy in natural time under time-reversal in the Olami-Feder-Christensen earthquake model. *Tectonophysics* **2011**, *513*, 49–53. [\[CrossRef\]](#)
9. Sarlis, N.V.; Varotsos, P.A.; Skordas, E.S. Flux avalanches in $\text{YBa}_2\text{Cu}_3\text{O}_{7-x}$ films and rice piles: Natural time domain analysis. *Phys. Rev. B* **2006**, *73*, 054504. [\[CrossRef\]](#)
10. Vallianatos, F.; Michas, G.; Benson, P.; Sammonds, P. Natural time analysis of critical phenomena: The case of acoustic emissions in triaxially deformed Etna basalt. *Physica A* **2013**, *392*, 5172–5178. [\[CrossRef\]](#)
11. Varotsos, C.A.; Tzanis, C. A new tool for the study of the ozone hole dynamics over Antarctica. *Atmos. Environ.* **2012**, *47*, 428–434. [\[CrossRef\]](#)
12. Varotsos, C.A.; Tzanis, C.; Cracknell, A.P. Precursory signals of the major El Niño Southern Oscillation events. *Theor. Appl. Climatol.* **2016**, *124*, 903–912. [\[CrossRef\]](#)
13. Varotsos, C.A.; Tzanis, C.G.; Sarlis, N.V. On the progress of the 2015–2016 El Niño event. *Atmos. Chem. Phys.* **2016**, *16*, 2007–2011. [\[CrossRef\]](#)
14. Varotsos, P.A.; Sarlis, N.V.; Skordas, E.S.; Lazaridou, M.S. Identifying sudden cardiac death risk and specifying its occurrence time by analyzing electrocardiograms in natural time. *Appl. Phys. Lett.* **2007**, *91*, 064106. [\[CrossRef\]](#)
15. Sarlis, N.V.; Skordas, E.S.; Varotsos, P.A. Heart rate variability in natural time and $1/f$ “noise”. *EPL* **2009**, *87*, 18003. [\[CrossRef\]](#)
16. Sarlis, N.V.; Christopoulos, S.R.G.; Bemplidaki, M.M. Change ΔS of the entropy in natural time under time reversal: Complexity measures upon change of scale. *EPL* **2015**, *109*, 18002. [\[CrossRef\]](#)
17. Baldoumas, G.; Peschos, D.; Tatsis, G.; Chronopoulos, S.K.; Christofilakis, V.; Kostarakis, P.; Varotsos, P.; Sarlis, N.V.; Skordas, E.S.; Bechlioulis, A.; et al. A Prototype Photoplethysmography Electronic Device that Distinguishes Congestive Heart Failure from Healthy Individuals by Applying Natural Time Analysis. *Electronics* **2019**, *8*, 1288. [\[CrossRef\]](#)
18. Baldoumas, G.; Peschos, D.; Tatsis, G.; Christofilakis, V.; Chronopoulos, S.K.; Kostarakis, P.; Varotsos, P.A.; Sarlis, N.V.; Skordas, E.S.; Bechlioulis, A.; et al. Remote sensing natural time analysis of heartbeat data by means of a portable photoplethysmography device. *Int. J. Remote Sens.* **2021**, *42*, 2292–2302. [\[CrossRef\]](#)
19. Niccolini, G.; Manuello, A.; Marchis, E.; Carpinteri, A. Signal frequency distribution and natural-time analyses from acoustic emission monitoring of an arched structure in the Castle of Racconigi. *Nat. Hazards Earth Syst. Sci.* **2017**, *17*, 1025–1032. [\[CrossRef\]](#)
20. Loukidis, A.; Pasiou, E.D.; Sarlis, N.V.; Triantis, D. Fracture analysis of typical construction materials in natural time. *Physica A* **2019**, *547*, 123831. [\[CrossRef\]](#)
21. Loukidis, A.; Perez-Oregon, J.; Pasiou, E.D.; Sarlis, N.V.; Triantis, D. Similarity of fluctuations in critical systems: Acoustic emissions observed before fracture. *Physica A* **2020**, *566*, 125622. [\[CrossRef\]](#)
22. Tanaka, H.K.; Varotsos, P.A.; Sarlis, N.V.; Skordas, E.S. A plausible universal behaviour of earthquakes in the natural time-domain. *Proc. Jpn. Acad. Ser. B Phys. Biol. Sci.* **2004**, *80*, 283–289. [\[CrossRef\]](#)
23. Varotsos, P.A.; Sarlis, N.V.; Tanaka, H.K.; Skordas, E.S. Similarity of fluctuations in correlated systems: The case of seismicity. *Phys. Rev. E* **2005**, *72*, 041103. [\[CrossRef\]](#) [\[PubMed\]](#)
24. Varotsos, P.A.; Sarlis, N.V.; Skordas, E.S.; Tanaka, H.K.; Lazaridou, M.S. Entropy of seismic electric signals: Analysis in the natural time under time reversal. *Phys. Rev. E* **2006**, *73*, 031114. [\[CrossRef\]](#) [\[PubMed\]](#)
25. Varotsos, P.A.; Sarlis, N.V.; Skordas, E.S.; Tanaka, H.K.; Lazaridou, M.S. Attempt to distinguish long-range temporal correlations from the statistics of the increments by natural time analysis. *Phys. Rev. E* **2006**, *74*, 021123. [\[CrossRef\]](#)
26. Varotsos, P.A.; Sarlis, N.V.; Skordas, E.S.; Lazaridou, M.S. Fluctuations, under time reversal, of the natural time and the entropy distinguish similar looking electric signals of different dynamics. *J. Appl. Phys.* **2008**, *103*, 014906. [\[CrossRef\]](#)
27. Sarlis, N.V.; Skordas, E.S.; Varotsos, P.A. Multiplicative cascades and seismicity in natural time. *Phys. Rev. E* **2009**, *80*, 022102. [\[CrossRef\]](#)
28. Sarlis, N.V.; Christopoulos, S.R.G. Natural time analysis of the Centennial Earthquake Catalog. *Chaos* **2012**, *22*, 023123. [\[CrossRef\]](#)
29. Sarlis, N.V.; Skordas, E.S.; Varotsos, P.A.; Nagao, T.; Kamogawa, M.; Tanaka, H.; Uyeda, S. Minimum of the order parameter fluctuations of seismicity before major earthquakes in Japan. *Proc. Natl. Acad. Sci. USA* **2013**, *110*, 13734–13738. [\[CrossRef\]](#)
30. Vallianatos, F.; Michas, G.; Papadakis, G. Non-extensive and natural time analysis of seismicity before the Mw6.4, October 12, 2013 earthquake in the South West segment of the Hellenic Arc. *Physica A* **2014**, *414*, 163–173. [\[CrossRef\]](#)
31. Sarlis, N.V.; Skordas, E.S.; Varotsos, P.A.; Nagao, T.; Kamogawa, M.; Uyeda, S. Spatiotemporal variations of seismicity before major earthquakes in the Japanese area and their relation with the epicentral locations. *Proc. Natl. Acad. Sci. USA* **2015**, *112*, 986–989. [\[CrossRef\]](#)
32. Huang, Q. Forecasting the epicenter of a future major earthquake. *Proc. Natl. Acad. Sci. USA* **2015**, *112*, 944–945. [\[CrossRef\]](#)

33. Rundle, J.B.; Turcotte, D.L.; Donnellan, A.; Grant Ludwig, L.; Luginbuhl, M.; Gong, G. Nowcasting earthquakes. *Earth Space Sci.* **2016**, *3*, 480–486. [\[CrossRef\]](#)
34. Potirakis, S.M.; Eftaxias, K.; Schekotov, A.; Yamaguchi, H.; Hayakawa, M. Criticality features in ultra-low frequency magnetic fields prior to the 2013 M6.3 Kobe earthquake. *Ann. Geophys.* **2016**, *59*, S0317. [\[CrossRef\]](#)
35. Christopoulos, S.R.G.; Sarlis, N.V. An Application of the Coherent Noise Model for the Prediction of Aftershock Magnitude Time Series. *Complexity* **2017**, *2017*, 6853892. [\[CrossRef\]](#)
36. Potirakis, S.M.; Asano, T.; Hayakawa, M. Criticality Analysis of the Lower Ionosphere Perturbations Prior to the 2016 Kumamoto (Japan) Earthquakes as Based on VLF Electromagnetic Wave Propagation Data Observed at Multiple Stations. *Entropy* **2018**, *20*, 199. [\[CrossRef\]](#)
37. Sarlis, N.V.; Skordas, E.S.; Varotsos, P.A. A remarkable change of the entropy of seismicity in natural time under time reversal before the super-giant M9 Tohoku earthquake on 11 March 2011. *EPL (Europhys. Lett.)* **2018**, *124*, 29001. [\[CrossRef\]](#)
38. Sarlis, N.V.; Skordas, E.S.; Varotsos, P.A.; Ramírez-Rojas, A.; Flores-Márquez, E.L. Natural time analysis: On the deadly Mexico M8.2 earthquake on 7 September 2017. *Physica A* **2018**, *506*, 625–634. [\[CrossRef\]](#)
39. Varotsos, P.A.; Sarlis, N.V.; Skordas, E.S. Natural time analysis: Important changes of the order parameter of seismicity preceding the 2011 M9 Tohoku earthquake in Japan. *EPL (Europhys. Lett.)* **2019**, *125*, 69001. [\[CrossRef\]](#)
40. Skordas, E.S.; Christopoulos, S.R.G.; Sarlis, N.V. Detrended fluctuation analysis of seismicity and order parameter fluctuations before the M7.1 Ridgecrest earthquake. *Nat. Hazards* **2020**, *100*, 697–711. [\[CrossRef\]](#)
41. Sarlis, N.V.; Skordas, E.S.; Christopoulos, S.R.G.; Varotsos, P.A. Natural Time Analysis: The Area under the Receiver Operating Characteristic Curve of the Order Parameter Fluctuations Minima Preceding Major Earthquakes. *Entropy* **2020**, *22*, 583. [\[CrossRef\]](#)
42. Yang, S.S.; Potirakis, S.M.; Sasmal, S.; Hayakawa, M. Natural Time Analysis of Global Navigation Satellite System Surface Deformation: The Case of the 2016 Kumamoto Earthquakes. *Entropy* **2020**, *22*, 674. [\[CrossRef\]](#)
43. Varotsos, P.A.; Skordas, E.S.; Sarlis, N.V. Fluctuations of the entropy change under time reversal: Further investigations on identifying the occurrence time of an impending major earthquake. *EPL (Europhys. Lett.)* **2020**, *130*, 29001. [\[CrossRef\]](#)
44. Varotsos, P.A.; Sarlis, N.V.; Skordas, E.S. Self-organized criticality and earthquake predictability: A long-standing question in the light of natural time analysis. *EPL (Europhys. Lett.)* **2020**, *132*, 29001. [\[CrossRef\]](#)
45. Vallianatos, F.; Michas, G.; Hloupis, G. Seismicity Patterns Prior to the Thessaly (Mw6.3) Strong Earthquake on 3 March 2021 in Terms of Multiresolution Wavelets and Natural Time Analysis. *Geosciences* **2021**, *11*, 379. [\[CrossRef\]](#)
46. Bak, P.; Christensen, K.; Danon, L.; Scanlon, T. Unified Scaling Law for Earthquakes. *Phys. Rev. Lett.* **2002**, *88*, 178501. [\[CrossRef\]](#)
47. Baiesi, M.; Paczuski, M. Scale-free networks of earthquakes and aftershocks. *Phys. Rev. E* **2004**, *69*, 066106. doi:10.1103/PhysRevE.69.066106. [\[CrossRef\]](#)
48. Davidsen, J.; Paczuski, M. Analysis of the Spatial Distribution Between Successive Earthquakes. *Phys. Rev. Lett.* **2005**, *94*, 048501. [\[CrossRef\]](#)
49. Corral, A. Long-Term Clustering, Scaling, and Universality in the Temporal Occurrence of Earthquakes. *Phys. Rev. Lett.* **2004**, *92*, 108501. [\[CrossRef\]](#)
50. Saichev, A.; Sornette, D. Vere-Jones' self-similar branching model. *Phys. Rev. E* **2005**, *72*, 056122. [\[CrossRef\]](#)
51. Livina, V.N.; Havlin, S.; Bunde, A. Memory in the Occurrence of Earthquakes. *Phys. Rev. Lett.* **2005**, *95*, 208501. [\[CrossRef\]](#)
52. Eichner, J.F.; Kantelhardt, J.W.; Bunde, A.; Havlin, S. Statistics of return intervals in long-term correlated records. *Phys. Rev. E* **2007**, *75*, 011128. [\[CrossRef\]](#) [\[PubMed\]](#)
53. Lennartz, S.; Livina, V.N.; Bunde, A.; Havlin, S. Long-term memory in earthquakes and the distribution of interoccurrence times. *EPL (Europhys. Lett.)* **2008**, *81*, 69001. [\[CrossRef\]](#)
54. Huang, Q. Seismicity changes prior to the Ms8.0 Wenchuan earthquake in Sichuan, China. *Geophys. Res. Lett.* **2008**, *35*, L23308. [\[CrossRef\]](#)
55. Lennartz, S.; Bunde, A.; Turcotte, D.L. Modelling seismic catalogues by cascade models: Do we need long-term magnitude correlations? *Geophys. J. Int.* **2011**, *184*, 1214–1222. [\[CrossRef\]](#)
56. Huang, Q. Retrospective investigation of geophysical data possibly associated with the Ms8.0 Wenchuan earthquake in Sichuan, China. *J. Asian Earth Sci.* **2011**, *41*, 421–427. [\[CrossRef\]](#)
57. Zaliapin, I.; Gabrielov, A.; Keilis-Borok, V.; Wong, H. Clustering analysis of seismicity and aftershock identification. *Phys. Rev. Lett.* **2008**, *101*, 018501. [\[CrossRef\]](#)
58. Tiampo, K.F.; Rundle, J.B.; Klein, W.; Holliday, J.; Sá Martins, J.S.; Ferguson, C.D. Ergodicity in natural earthquake fault networks. *Phys. Rev. E* **2007**, *75*, 066107. [\[CrossRef\]](#)
59. Lippiello, E.; Godano, C.; de Arcangelis, L. Dynamical Scaling in Branching Models for Seismicity. *Phys. Rev. Lett.* **2007**, *98*, 098501. [\[CrossRef\]](#)
60. Tenenbaum, J.N.; Havlin, S.; Stanley, H.E. Earthquake networks based on similar activity patterns. *Phys. Rev. E* **2012**, *86*, 046107. [\[CrossRef\]](#)
61. Lippiello, E.; Godano, C.; de Arcangelis, L. The earthquake magnitude is influenced by previous seismicity. *Geophys. Res. Lett.* **2012**, *39*, L05309. [\[CrossRef\]](#)
62. Huang, Q.; Ding, X. Spatiotemporal variations of seismic quiescence prior to the 2011 M 9.0 Tohoku earthquake revealed by an improved region-time-length algorithm. *Bull. Seismol. Soc. Am.* **2012**, *102*, 1878–1883. [\[CrossRef\]](#)
63. Bunde, A.; Lennartz, S. Long-Term Correlations in Earth Sciences. *Acta Geophys.* **2012**, *60*, 562–588. [\[CrossRef\]](#)

64. Tiampo, K.F.; Shcherbakov, R. Seismicity-based earthquake forecasting techniques: Ten years of progress. *Tectonophysics* **2012**, *522–523*, 89–121. [\[CrossRef\]](#)
65. Zaliapin, I.; Ben-Zion, Y. Earthquake clusters in southern California I: Identification and stability. *J. Geophys. Res. Solid Earth* **2013**, *118*, 2847–2864. [\[CrossRef\]](#)
66. Zaliapin, I.; Ben-Zion, Y. Earthquake clusters in southern California II: Classification and relation to physical properties of the crust. *J. Geophys. Res. Solid Earth* **2013**, *118*, 2865–2877. [\[CrossRef\]](#)
67. Batac, R.C.; Kantz, H. Observing spatio-temporal clustering and separation using interevent distributions of regional earthquakes. *Nonlin. Processes Geophys.* **2014**, *21*, 735–744. [\[CrossRef\]](#)
68. Zaliapin, I.; Ben-Zion, Y. Artefacts of earthquake location errors and short-term incompleteness on seismicity clusters in southern California. *Geophys. J. Int.* **2015**, *202*, 1949–1968. [\[CrossRef\]](#)
69. de Arcangelis, L.; Godano, C.; Grasso, J.R.; Lippiello, E. Statistical physics approach to earthquake occurrence and forecasting. *Phys. Rep.* **2016**, *628*, 1–91. [\[CrossRef\]](#)
70. Turcotte, D.L. *Fractals and Chaos in Geology and Geophysics*, 2nd ed.; Cambridge University Press: Cambridge, UK, 1997. [\[CrossRef\]](#)
71. Scholz, C.H. *The mechanics of Earthquakes and Faulting*, 2nd ed.; Cambridge University Press: Cambridge, UK, 2002. [\[CrossRef\]](#)
72. Holliday, J.R.; Rundle, J.B.; Turcotte, D.L.; Klein, W.; Tiampo, K.F.; Donnellan, A. Space-Time Clustering and Correlations of Major Earthquakes. *Phys. Rev. Lett.* **2006**, *97*, 238501. [\[CrossRef\]](#)
73. Sornette, D. *Critical Phenomena in the Natural Sciences: Chaos, Fractals, Selforganization, and Disorder: Concepts and Tools*; Springer: Berlin/Heidelberg, Germany, 2000. [\[CrossRef\]](#)
74. Carlson, J.M.; Langer, J.S.; Shaw, B.E. Dynamics of earthquake faults. *Rev. Mod. Phys.* **1994**, *66*, 657–670. doi:10.1103/RevModPhys.66.657. [\[CrossRef\]](#)
75. Xia, J.; Gould, H.; Klein, W.; Rundle, J.B. Near-mean-field behavior in the generalized Burridge-Knopoff earthquake model with variable-range stress transfer. *Phys. Rev. E* **2008**, *77*, 031132. [\[CrossRef\]](#)
76. Rundle, J.B.; Klein, W.; Gross, S. Dynamics of a Traveling Density Wave Model for Earthquakes. *Phys. Rev. Lett.* **1996**, *76*, 4285–4288. [\[CrossRef\]](#)
77. Fisher, D.S.; Dahmen, K.; Ramanathan, S.; Ben-Zion, Y. Statistics of Earthquakes in Simple Models of Heterogeneous Faults. *Phys. Rev. Lett.* **1997**, *78*, 4885–4888. [\[CrossRef\]](#)
78. Rundle, J.B.; Turcotte, D.L.; Shcherbakov, R.; Klein, W.; Sammis, C. Statistical physics approach to understanding the multiscale dynamics of earthquake fault systems. *Rev. Geophys.* **2003**, *41*, 1019. [\[CrossRef\]](#)
79. Landau, L.D.; Lifshitz, E.M. *Statistical Physics*, 3rd ed.; Pergamon Press: Oxford, UK, 1980.
80. Flores-Márquez, E.L.; Ramírez-Rojas, A.; Perez-Oregon, J.; Sarlis, N.V.; Skordas, E.S.; Varotsos, P.A. Natural Time Analysis of Seismicity within the Mexican Flat Slab before the M7.1 Earthquake on 19 September 2017. *Entropy* **2020**, *22*, 730. [\[CrossRef\]](#)
81. Varotsos, P.A.; Sarlis, N.V.; Skordas, E.S. Remarkable changes in the distribution of the order parameter of seismicity before mainshocks. *EPL* **2012**, *100*, 39002. [\[CrossRef\]](#)
82. Varotsos, P.A.; Sarlis, N.V.; Skordas, E.S. Scale-specific order parameter fluctuations of seismicity in natural time before mainshocks. *EPL* **2011**, *96*, 59002. [\[CrossRef\]](#)
83. Varotsos, P.A.; Sarlis, N.V.; Skordas, E.S.; Lazaridou, M.S. Seismic Electric Signals: An additional fact showing their physical interconnection with seismicity. *Tectonophysics* **2013**, *589*, 116–125. [\[CrossRef\]](#)
84. Varotsos, P.; Alexopoulos, K.; Nomicos, K. Seismic Electric Currents. *Pract. Athens Acad.* **1981**, *56*, 277–286.
85. Varotsos, P.; Alexopoulos, K. Physical Properties of the variations of the electric field of the Earth preceding earthquakes, I. *Tectonophysics* **1984**, *110*, 73–98. [\[CrossRef\]](#)
86. Varotsos, P.; Alexopoulos, K. Physical Properties of the variations of the electric field of the Earth preceding earthquakes, II. *Tectonophysics* **1984**, *110*, 99–125. [\[CrossRef\]](#)
87. Varotsos, P.; Alexopoulos, K. *Thermodynamics of Point Defects and their Relation with Bulk Properties*; North Holland: Amsterdam, The Netherlands, 1986.
88. Varotsos, P.; Lazaridou, M. Latest aspects of earthquake prediction in Greece based on Seismic Electric Signals. *Tectonophysics* **1991**, *188*, 321–347. [\[CrossRef\]](#)
89. Varotsos, P.; Alexopoulos, K.; Lazaridou, M. Latest aspects of earthquake prediction in Greece based on Seismic Electric Signals, II. *Tectonophysics* **1993**, *224*, 1–37. [\[CrossRef\]](#)
90. Varotsos, P. *The Physics of Seismic Electric Signals*; TERRAPUB: Tokyo, Japan, 2005; p. 338.
91. Sarlis, N.V.; Christopoulos, S.R.G.; Skordas, E.S. Minima of the fluctuations of the order parameter of global seismicity. *Chaos* **2015**, *25*, 063110. [\[CrossRef\]](#)
92. Sarlis, N.V.; Skordas, E.S.; Christopoulos, S.R.G.; Varotsos, P.A. Statistical Significance of Minimum of the Order Parameter Fluctuations of Seismicity Before Major Earthquakes in Japan. *Pure Appl. Geophys.* **2016**, *173*, 165–172. [\[CrossRef\]](#)
93. Sarlis, N.V.; Skordas, E.S.; Mintzels, A.; Papadopoulou, K.A. Micro-scale, mid-scale, and macro-scale in global seismicity identified by empirical mode decomposition and their multifractal characteristics. *Sci. Rep.* **2018**, *8*, 9206. [\[CrossRef\]](#)
94. Christopoulos, S.R.G.; Skordas, E.S.; Sarlis, N.V. On the Statistical Significance of the Variability Minima of the Order Parameter of Seismicity by Means of Event Coincidence Analysis. *Appl. Sci.* **2020**, *10*, 662. [\[CrossRef\]](#)
95. Varotsos, P.A.; Sarlis, N.V.; Skordas, E.S. Study of the temporal correlations in the magnitude time series before major earthquakes in Japan. *J. Geophys. Res. Space Phys.* **2014**, *119*, 9192–9206. [\[CrossRef\]](#)

96. Sarlis, N.V.; Skordas, E.S.; Varotsos, P.A.; Ramírez-Rojas, A.; Flores-Márquez, E.L. Identifying the Occurrence Time of the Deadly Mexico M8.2 Earthquake on 7 September 2017. *Entropy* **2019**, *21*, 301. [\[CrossRef\]](#)
97. Watts, D.J.; Strogatz, S.H. Collective dynamics of ‘small-world’ networks. *Nature* **1998**, *393*, 440–442. [\[CrossRef\]](#)
98. Albert, R.; Barabási, A.L. Statistical mechanics of complex networks. *Rev. Mod. Phys.* **2002**, *74*, 47–97. [\[CrossRef\]](#)
99. Dorogovtsev, S.N.; Goltsev, A.V.; Mendes, J.F.F. Critical phenomena in complex networks. *Rev. Mod. Phys.* **2008**, *80*, 1275–1335. [\[CrossRef\]](#)
100. Newman, M.E.J. *Networks: An Introduction*; Oxford University Press: Oxford, UK, 2010. [\[CrossRef\]](#)
101. Di Muro, M.A.; La Rocca, C.E.; Stanley, H.E.; Havlin, S.; Braunstein, L.A. Recovery of Interdependent Networks. *Sci. Rep.* **2016**, *6*, 22834. [\[CrossRef\]](#)
102. Baiesi, M.; Paczuski, M. Complex networks of earthquakes and aftershocks. *Nonlin. Processes Geophys.* **2005**, *12*, 1–11. [\[CrossRef\]](#)
103. Baiesi, M. Scaling and precursor motifs in earthquake networks. *Physica A* **2006**, *360*, 534–542. [\[CrossRef\]](#)
104. Davidsen, J.; Grassberger, P.; Paczuski, M. Networks of recurrent events, a theory of records, and an application to finding causal signatures in seismicity. *Phys. Rev. E* **2008**, *77*, 066104. [\[CrossRef\]](#)
105. Krishna Mohan, T.R.; Revathi, P.G. Earthquake correlations and networks: A comparative study. *Phys. Rev. E* **2011**, *83*, 046109. [\[CrossRef\]](#)
106. Telesca, L.; Lovallo, M. Analysis of seismic sequences by using the method of visibility graph. *EPL (Europhys. Lett.)* **2012**, *97*, 50002. [\[CrossRef\]](#)
107. Telesca, L.; Lovallo, M.; Ramirez-Rojas, A.; Flores-Marquez, L. Investigating the time dynamics of seismicity by using the visibility graph approach: Application to seismicity of Mexican subduction zone. *Physica A* **2013**, *392*, 6571–6577. [\[CrossRef\]](#)
108. Telesca, L.; Lovallo, M.; Ramirez-Rojas, A.; Flores-Marquez, L. Relationship between the Frequency Magnitude Distribution and the Visibility Graph in the Synthetic Seismicity Generated by a Simple Stick-Slip System with Asperities. *PLoS ONE* **2014**, *9*, e106233. [\[CrossRef\]](#)
109. Telesca, L.; Lovallo, M.; Aggarwal, S.; Khan, P. Precursory signatures in the visibility graph analysis of seismicity: An application to the Kachchh (Western India) seismicity. *Phys. Chem. Earth* **2015**, *85–86*, 195–200. [\[CrossRef\]](#)
110. Telesca, L.; Lovallo, M.; Aggarwal, S.K.; Khan, P.K.; Rastogi, B.K. Visibility Graph Analysis of the 2003–2012 Earthquake Sequence in the Kachchh Region of Western India. *Pure Appl. Geophys.* **2016**, *173*, 125–132. [\[CrossRef\]](#)
111. Telesca, L.; Cheldize, T. Visibility graph analysis of seismicity around Enguri high arch dam, Caucasus. *Bull. Seismol. Soc. Am.* **2018**, *108*, 3141–3147. [\[CrossRef\]](#)
112. Chorozoglou, D.; Kugiumtzis, D.; Papadimitriou, E. Application of complex network theory to the recent foreshock sequences of Methoni (2008) and Kefalonia (2014) in Greece. *Acta Geophys.* **2017**, *65*, 543–553. [\[CrossRef\]](#)
113. Chorozoglou, D.; Kugiumtzis, D.; Papadimitriou, E. Testing the structure of earthquake networks from multivariate time series of successive main shocks in Greece. *Physica A* **2018**, *499*, 28–39. [\[CrossRef\]](#)
114. Chorozoglou, D.; Papadimitriou, E.; Kugiumtzis, D. Investigating small-world and scale-free structure of earthquake networks in Greece. *Chaos Solitons Fractals* **2019**, *122*, 143–152. [\[CrossRef\]](#)
115. Mintzels, A.; Sarlis, N. Minima of the fluctuations of the order parameter of seismicity and earthquake networks based on similar activity patterns. *Physica A* **2019**, *527*, 121293. [\[CrossRef\]](#)
116. Pasari, S. Nowcasting Earthquakes in the Bay of Bengal Region. *Pure Appl. Geophys.* **2019**, *176*, 1417–1432. [\[CrossRef\]](#)
117. Rundle, J.B.; Luginbuhl, M.; Giguere, A.; Turcotte, D.L. Natural Time, Nowcasting and the Physics of Earthquakes: Estimation of Seismic Risk to Global Megacities. *Pure Appl. Geophys.* **2018**, *175*, 647–660. [\[CrossRef\]](#)
118. Luginbuhl, M.; Rundle, J.B.; Hawkins, A.; Turcotte, D.L. Nowcasting Earthquakes: A Comparison of Induced Earthquakes in Oklahoma and at the Geysers, California. *Pure Appl. Geophys.* **2018**, *175*, 49–65. [\[CrossRef\]](#)
119. Luginbuhl, M.; Rundle, J.B.; Turcotte, D.L. Natural Time and Nowcasting Earthquakes: Are Large Global Earthquakes Temporally Clustered? *Pure Appl. Geophys.* **2018**, *175*, 661–670. [\[CrossRef\]](#)
120. Luginbuhl, M.; Rundle, J.B.; Turcotte, D.L. Natural time and nowcasting induced seismicity at the Groningen gas field in the Netherlands. *Geophys. J. Int.* **2018**, *215*, 753–759. [\[CrossRef\]](#)
121. Rundle, J.B.; Luginbuhl, M.; Khapikova, P.; Turcotte, D.L.; Donnellan, A.; McKim, G. Nowcasting Great Global Earthquake and Tsunami Sources. *Pure Appl. Geophys.* **2020**, *177*, 359–368. [\[CrossRef\]](#)
122. Rundle, J.B.; Giguere, A.; Turcotte, D.L.; Crutchfield, J.P.; Donnellan, A. Global Seismic Nowcasting With Shannon Information Entropy. *Earth Space Sci.* **2019**, *6*, 191–197. [\[CrossRef\]](#)
123. Pasari, S.; Sharma, Y. Contemporary Earthquake Hazards in the West-Northwest Himalaya: A Statistical Perspective through Natural Times. *Seismol. Res. Lett.* **2020**, *91*, 3358–3369. [\[CrossRef\]](#)
124. Perez-Oregon, J.; Muñoz Diosdado, A.; Rudolf-Navarro, A.H.; Angulo-Brown, F. A Simple Model to Relate the Elastic Ratio Gamma of a Critically Self-Organized Spring-Block Model with the Age of a Lithospheric Downgoing Plate in a Subduction Zone. *Entropy* **2020**, *22*, 868. [\[CrossRef\]](#)
125. Rundle, J.B.; Donnellan, A.; Fox, G.; Crutchfield, J.P. Nowcasting Earthquakes by Visualizing the Earthquake Cycle with Machine Learning: A Comparison of Two Methods. *Surv. Geophys.* **2021**, 1–19. [\[CrossRef\]](#)
126. Rundle, J.B.; Donnellan, A.; Fox, G.; Crutchfield, J.P.; Granat, R. Nowcasting Earthquakes: Imaging the Earthquake Cycle in California with Machine Learning. *Earth Space Sci.* **2021**, e2021EA001757. [\[CrossRef\]](#)

127. United States Geological Survey, Earthquake Hazards Program. Search Earthquake Catalog. Available online: <https://earthquake.usgs.gov/earthquakes/search/> (accessed on 9 February 2021).
128. Taymaz, T.; Jackson, J.; McKenzie, D. Active tectonics of the north and central Aegean Sea. *Geophys. J. Int.* **1991**, *106*, 433–490. [CrossRef]
129. Devoti, R.; Ferraro, C.; Gueguen, E.; Lanotte, R.; Luceri, V.; Nardi, A.; Pacione, R.; Rutigliano, P.; Sciarretta, C.; Vespe, F. Geodetic control on recent tectonic movements in the central Mediterranean area. *Tectonophysics* **2002**, *346*, 151–167. doi:10.1016/S0040-1951(01)00277-3. [CrossRef]
130. Kassaras, I.; Kapetanidis, V.; Ganas, A.; Tzanis, A.; Kosma, C.; Karakostas, A.; Valkaniotis, S.; Chailas, S.; Kouskouna, V.; Papadimitriou, P. The New Seismotectonic Atlas of Greece (v1.0) and Its Implementation. *Geosciences* **2020**, *10*, 447. [CrossRef]
131. McKenzie, D. Active tectonics of the Alpine—Himalayan belt: The Aegean Sea and surrounding regions. *Geophys. J. Int.* **1978**, *55*, 217–254. [CrossRef]
132. Bird, P. An updated digital model of plate boundaries. *Geochem. Geophys. Geosyst.* **2003**, *4*, 1027. [CrossRef]
133. Kanamori, H. Quantification of Earthquakes. *Nature* **1978**, *271*, 411–414. [CrossRef]
134. Sarlis, N.V.; Skordas, E.S.; Varotsos, P.A. Order parameter fluctuations of seismicity in natural time before and after mainshocks. *EPL* **2010**, *91*, 59001. [CrossRef]
135. Goldenfeld, N. *Lectures on Phase Transitions and the Renormalization Group*; CRC Press, Taylor & Francis Group: Boca Raton, FL, USA, 2018.
136. Sarlis, N.V.; Skordas, E.S. Study in Natural Time of Geoelectric Field and Seismicity Changes Preceding the Mw6.8 Earthquake on 25 October 2018 in Greece. *Entropy* **2018**, *20*, 882. [CrossRef]
137. Ferguson, C.D.; Klein, W.; Rundle, J.B. Spinodals, scaling, and ergodicity in a threshold model with long-range stress transfer. *Phys. Rev. E* **1999**, *60*, 1359–1373. [CrossRef]
138. Tiampo, K.F.; Rundle, J.B.; Klein, W.; Martins, J.S.S.; Ferguson, C.D. Ergodic Dynamics in a Natural Threshold System. *Phys. Rev. Lett.* **2003**, *91*, 238501. [CrossRef]
139. Press, W.H.; Teukolsky, S.; Vetterling, W.; Flannery, B.P. *Numerical Recipes in FORTRAN*; Cambridge University Press: New York, NY, USA, 1992; p. 963.
140. Weisstein, E.W. Circle-Circle Intersection. From MathWorld—A Wolfram Web Resource. 2021. Available online: <https://mathworld.wolfram.com/Circle-CircleIntersection.html> (accessed on 15 September 2021).
141. Sarlis, N.V.; Skordas, E.S.; Varotsos, P.A.; Ramírez-Rojas, A.; Flores-Márquez, E.L. Investigation of the temporal correlations between earthquake magnitudes before the Mexico M8.2 earthquake on 7 September 2017. *Physica A* **2019**, *517*, 475–483. [CrossRef]
142. Lazaridou-Varotsos, M.S. *Earthquake Prediction by Seismic Electric Signals: The success of the VAN method over thirty years*; Springer Praxis Books: Berlin/Heidelberg, Germany, 2013.
143. Varotsos, P.; Sarlis, N.; Skordas, E. A note on the spatial extent of the Volos SES sensitive site. *Acta Geophys. Pol.* **2001**, *49*, 425–435.
144. Sarlis, N.V.; Skordas, E.S.; Lazaridou, M.S.; Varotsos, P.A. Investigation of seismicity after the initiation of a Seismic Electric Signal activity until the main shock. *Proc. Jpn. Acad. Ser. B Phys. Biol. Sci.* **2008**, *84*, 331–343. [CrossRef] [PubMed]
145. Xu, G.; Han, P.; Huang, Q.; Hattori, K.; Febriani, F.; Yamaguchi, H. Anomalous behaviors of geomagnetic diurnal variations prior to the 2011 off the Pacific coast of Tohoku earthquake (Mw9.0). *J. Asian Earth Sci.* **2013**, *77*, 59–65. [CrossRef]
146. Han, P.; Hattori, K.; Xu, G.; Ashida, R.; Chen, C.H.; Febriani, F.; Yamaguchi, H. Further investigations of geomagnetic diurnal variations associated with the 2011 off the Pacific coast of Tohoku earthquake (Mw 9.0). *J. Asian Earth Sci.* **2015**, *114*, 321–326. [CrossRef]
147. Han, P.; Hattori, K.; Huang, Q.; Hirooka, S.; Yoshino, C. Spatiotemporal characteristics of the geomagnetic diurnal variation anomalies prior to the 2011 Tohoku earthquake (Mw 9.0) and the possible coupling of multiple pre-earthquake phenomena. *J. Asian Earth Sci.* **2016**, *129*, 13–21. [CrossRef]
148. Skordas, E.S.; Sarlis, N.V.; Varotsos, P.A. Identifying the occurrence time of an impending major earthquake by means of the fluctuations of the entropy change under time reversal. *EPL (Europhys. Lett.)* **2019**, *128*, 49001. [CrossRef]
149. Williams, T.; Kelley, C. Gnuplot 4.6: An Interactive Plotting Program. 2014. Available online: <http://www.gnuplot.info> (accessed on 28 February 2014).
150. Metzger, D.R. GEODAS Coastline Extractor, Version 1.1.3.1. 2014. Available online: http://www.ngdc.noaa.gov/mgg/dat/geodas/software/mswindows/geodas-ng_setup.exe (accessed on 11 February 2015).