



OPEN Complexity measure in natural time analysis identifying the accumulation of stresses before major earthquakes

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Here, we suggest a procedure through which one can identify when the accumulation of stresses before major earthquakes (EQs) (of magnitude $M \geq 8.2$ or larger) occurs. Analyzing the seismicity in natural time, which is a new concept of time, we study the evolution of the fluctuations of the entropy change of seismicity under time reversal for various scales of different length i (number of events). Although the stress might be accumulating throughout the entire process of EQ preparation due to tectonic loading, here we find that the proposed complexity measure reveals different stress accumulation characteristics from those in the long-term background when the system approaches the critical stage. Specifically, we find that anomalous intersections between scales of different i are observed upon approaching a major EQ occurrence. The investigation is presented for the seismicity in Japan since 1984 including the $M9$ Tohoku EQ on 11 March 2011, which is the largest EQ ever recorded there, as well as for the seismicity before 2017 Chiapas $M8.2$ EQ, which is Mexico's largest EQ in more than a century. Based on this new complexity measure, a preprint submitted on 5 December 2023 anticipated the 1 January 2024 $M7.6$ EQ in Japan.

Keywords Entropy, Time-series, Earthquakes, Complexity, Geophysics

It is widely known^{1–3} that earthquake (EQ) occurrences exhibit complex correlations in time, space and magnitude (e.g.,^{4–9}) and the observed EQ scaling laws¹⁰ indicate the existence of phenomena closely associated with the proximity of the system to a critical point. In the 1980s, the observation of Seismic Electric Signals (SES), which are low frequency transient changes of the electric field of the Earth preceding EQs, was reported^{11–13}. Many SESs observed within a short time are termed SES activity¹⁴ being accompanied by Earth's magnetic field variations¹⁵ mainly on the z-component^{16,17}. These observations have been motivated by a physical model for SES generation, which enables the explanation of the simultaneous detection of additional transient multidisciplinary phenomena before the EQ rupture¹⁸. This physical model is termed “pressure stimulated polarization currents” (PSPC) model^{11,12,19,20} and could be summarized as follows: In the Earth, electric dipoles are always present¹⁹ due to lattice imperfections (point and linear defects) in the ionic constituents of rocks and exhibit initially random orientations at the future focal region of an EQ, where the stress, σ , starts to gradually increase. This is called stage A. When this stress accumulation achieves a critical value, the electric dipoles exhibit a cooperative orientation resulting in the emission of a SES activity (cf. cooperativity is a hallmark of criticality²¹). This is called stage B. Uyeda et al.²² mentioned that the PSPC model is unique in the following sense: In the PSPC model the SES is generated spontaneously during the gradual increase of stress, while other models that have been proposed for the explanation of the SES generation require a sudden change of stress such as microfracturing. Uyeda et al.²² also explained that a direct observation of the spontaneous SES emission cannot be verified in view of the following: laboratory measurements are admittedly hard to perform because one would need to run an electrically well insulated stress machine for a long time with extremely low stress rates until PSPC flows.

The criticality of SES activities has been ascertained by employing natural time analysis (NTA)^{23–25}, which has been introduced in 2001²⁶ based on a new concept of time termed natural time. NTA enables the uncovering

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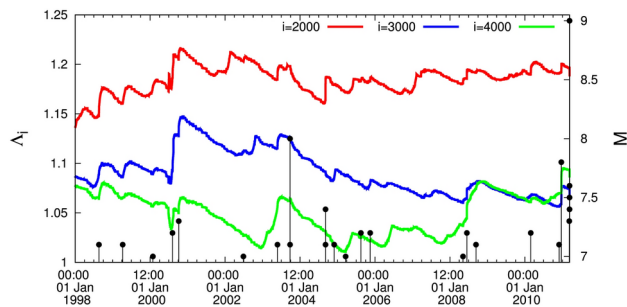


Figure 1. The complexity measure Δ_i for various scales $i = 2000$ (red), 3000 (blue), and 4000 (green) versus the conventional time from 1 January 1998 until the M9 Tohoku EQ.

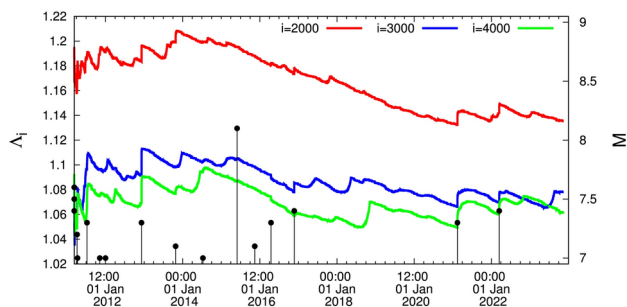


Figure 2. The complexity measure Δ_i for various scales $i = 2000$ (red), 3000 (blue), and 4000 (green) versus the conventional time from 15:00 LT on 11 March 2011 until 15 November 2023. The strongest EQ during this period is the Ogasawara EQ, see the text.

of hidden properties in time series of complex systems and can identify when the system approaches the critical point (for EQs the mainshock occurrence is considered the new phase)^{3,27}.

We note that fluctuations are the dominant feature of criticality^{28,29} and close enough to the critical point they become as important as the mean. In particular, the fluctuations of the entropy change under time reversal computed by Eq. (4) are important in order to identify the approach to criticality for major EQs like the M9 Tohoku EQ in Japan in 2011³⁰ and the M8.2 EQ in Mexico on 7 September 2017³¹ (see also Chapters 8.2 and 8.4 of Ref.²⁷).

Although the stress might be accumulating throughout the entire EQ preparation, it is our purpose here to identify a precursor when the system approaches the critical stage that exhibits different stress accumulation characteristics from those in the long term background.

Results

Here, we follow the new concept of time introduced in 2001, termed natural time, in which the entropy S changes to S_- upon reversing the time arrow (see “Methods”). Then a new complexity measure Λ is defined, which quantifies the fluctuations of the quantity $\Delta S \equiv S - S_-$ when analysing the earthquake data. We then find that such a procedure identifies when the accumulation of stresses occurs well before the occurrence of major EQs.

The results from Japan concerning the study of Δ_i are plotted in Figs. 1, 2, and 3 by starting the computation from 1 January 1984 for the scales $i = 2000$, 3000, and 4000 events. After a careful inspection of these figures the following comments are now in order:

Results from 1 January 1998 until the M9 Tohoku EQ occurrence on 11 March 2011

During almost a decade, i.e., during the period from 1 January 1998 until the M7.2 EQ on 14 June 2008, there exists no intersection between the curves of the three scales $i = 2000$, 3000, and 4000 events since the scale $i = 2000$ events lies in the highest level, the scale $i = 3000$ events in the middle level and the scale $i = 4000$ events in the lowest level. Approximately, from the latter date the curve of the scale $i = 4000$ events shows a clear increase, thus finally almost overlapping the curve of the scale $i = 3000$ events until almost 5 August 2010. From thereon, however, the curve corresponding to $i = 4000$ events exceeds the one of 3000 events (cf. at this date the two curves intersect) and subsequently it exhibits an abrupt increase upon the occurrence of the M7.8 EQ on 22 December 2010 in southern Japan at 27.05° N 143.94° E, which constitutes an evident intersection. Almost $2\frac{1}{2}$ months after the completion of this intersection the M9 EQ occurred.

Remarkably, on this date (22 December 2010) of the abrupt increase of Δ_i additional facts are observed: The abrupt increase conforms to the seminal work by Lifshitz and Slyozov³² and independently by Wagner³³ (LSW) for phase transitions showing that the characteristic size of the minority phase droplets exhibits a scaling

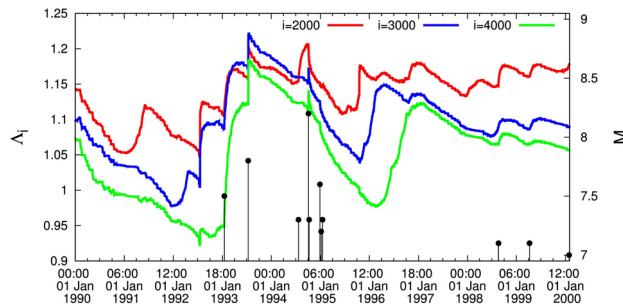


Figure 3. The complexity measure Λ_i for various scales $i = 2000$ (red), 3000 (blue), and 4000 (green) versus the conventional time from 1 January 1990 until 1 February 2000.

behavior in which time (t) growth has the form $A(t - t_0)^{1/3}$. It was found that the increase $\Delta\Lambda_i$ of Λ_i follows the latter form and that the prefactors A are proportional to the scale i , while the exponent ($1/3$) is independent of i ³⁰. Furthermore, the Tsallis³⁴ entropic index q exhibits a simultaneous increase with the same exponent ($1/3$)³⁰.

In addition, a minimum ΔS_{min} of the entropy change ΔS of seismicity in the entire Japanese region under time reversal was identified by Sarlis et al.³⁵, who also showed that the probability to obtain such a minimum by chance is approximately 3% thus demonstrating that it is statistically significant. The robustness of the appearance of ΔS_{min} on 22 December 2010 upon changing the EQ depth, the EQ magnitude threshold, and the size of the area investigated has been documented³⁵. Such a minimum is of precursory nature, signaling that a large EQ is impending according to the NTA of the Olami-Feder-Christensen (OFC) model for earthquakes³⁶, which is probably³⁷ the most studied non-conservative self-organized criticality (SOC) model, originated by a simplification of the Burridge and Knopoff spring-block model³⁸. In the OFC model, NTA showed that ΔS exhibits a clear minimum³ before a large avalanche, which corresponds to a large EQ.

Finally, studying the fluctuations β of κ_1 of seismicity in the entire Japanese region $N_{25}^{46}E_{125}^{148}$ versus the conventional time from 1 January 1984 until the Tohoku EQ occurrence on 11 March 2011, we find³⁹ a large fluctuation of β upon the occurrence of the $M_{7.8}$ EQ on 22 December 2010. This finding was also checked for several scales from $i = 150$ to 500 events, which also revealed the following³⁹: upon increasing i it is observed (see Figs. 2b and 4e of Ref.⁴⁰) that the increase $\Delta\beta_i$ of the β_i fluctuation on 22 December 2010 becomes distinctly larger—obeying the interrelation $\Delta\beta_i = 0.5 \ln(i/114.3)$ —which does not happen (see Fig. 4a–d of Ref.⁴⁰) for the increases in the β fluctuations upon the occurrences of all other shallow EQs in Japan of magnitude 7.6 or larger during the period from 1 January 1984 to the time of the M_9 Tohoku EQ. This interrelation $\Delta\beta_i = 0.5 \ln(i/114.3)$, see Fig. 2g,h of Ref.³⁹, has a functional form strikingly reminiscent of the one discussed by Penrose et al.⁴¹ in computer simulations of phase separation kinetics using the ideas of Lifshitz and Slyozov³², see their Eq. (33) which is also due to Lifshitz and Slyozov. Hence, the β fluctuation on 22 December 2010 accompanying the minimum ΔS_{min} is unique.

Results from 15:00 LT on 11 March 2011 until now

During this period, a $M_w 7.9$ EQ occurred beneath the Ogasawara (Bonin) Islands on 30 May 2015 as depicted in Fig. 2. It occurred at 680 km depth in an area without any known historical seismicity and caused significant shaking over a broad area of Japan at epicentral distances in the range 1000–2000 km. It was the first EQ felt in every Japanese prefecture since intensity observations began in 1884. This is the deepest EQ ever detected (<https://www.nationalgeographic.com/science/article/deepest-earthquake-ever-detected-struck-467-miles-beneath-japan>) and was also noted⁴² that globally, this is the deepest (680 km centroid depth) event with $M_w > 7.8$ in the seismological records.

The Ogasawara EQ has not been followed by an appreciably stronger EQ in contrast to the $M_{7.8}$ Chichi-jima shallow EQ which occurred also at Bonin islands at $27.05^\circ N$ $143.94^\circ E$ on 22 December 2010, almost three months before the M_9 Tohoku EQ. This could be understood as follows⁴³: Upon the occurrence of the Chichi-jima EQ the following facts have been observed: First, according to Ref.³⁰ the complexity measures Λ_{2000} , Λ_{3000} and Λ_{4000} , i.e., the Λ_i values at the natural time window lengths (scales) $i = 2000$, 3000 and 4000 events, respectively, show a strong abrupt increase $\Delta\Lambda_i$ in Fig. 7 of Ref.³⁰ on 22 December 2010 and just after the EQ occurrence exhibiting a scaling behavior of the form $\Delta\Lambda_i = A(t - t_0)^c$ (where the exponent c is very close to $1/3$ and t_0 is approximately 0.2 days after the $M_{7.8}$ EQ occurrence), which conforms to LSW. Second, the order parameter fluctuations showed a unique change³⁹, i.e., an increase $\Delta\beta_i$, which exhibits a functional form consistent with the LSW theory and the subsequent work of Penrose et al.⁴¹ obeying the interrelation $\Delta\beta_i = 0.5 \ln(i/114.3)$, see Fig. 2g,h of Ref.³⁹. Such a behavior has not been observed along with the occurrence of either the Ogasawara EQ or any other shallow EQs in Japan of magnitude 7.6 or larger during the period from 1 January 1984 to the time of the M_9 Tohoku EQ³⁹ (including also the EQ that occurred on 1 January 2024 discussed later).

An additional important fact is the following: On 27 October 2022, the curve corresponding to the scale $i = 4000$ events (green) intersects the one for the scale $i = 3000$ (blue), but the latter on 27 June 2023 recovers, see Fig. 4 (we shall return to this important fact later on). This phenomenon has been followed very carefully—since it started as described in Ref.⁴⁴—compared to the one that preceded the M_9 Tohoku EQ (Fig. 5).

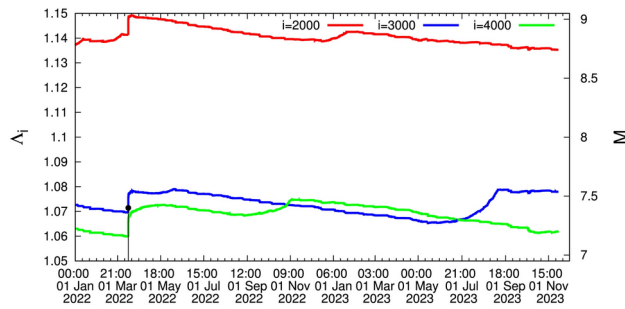


Figure 4. The complexity measure Λ_i for various scales $i = 2000$ (red), 3000 (blue), and 4000 (green) versus the conventional time from 1 January 2022 until 15 November 2023.

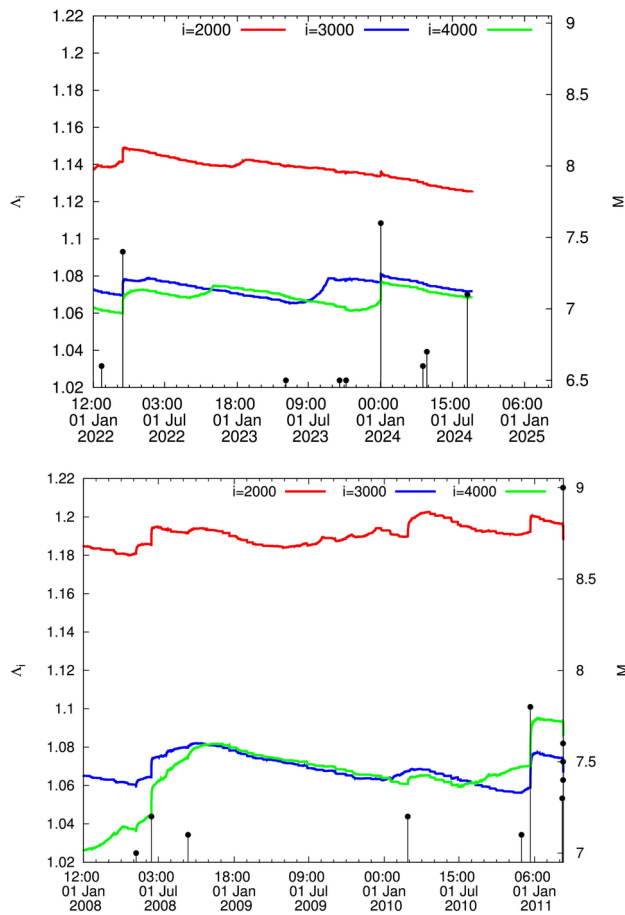


Figure 5. The complexity measure Λ_i for various scales $i = 2000$ (red), 3000 (blue), and 4000 (green) before the $M7.6$ EQ on the west coast of Japan on 1 January 2024 (upper panel) and the $M9$ Tohoku EQ on 11 March 2011 (lower panel).

Results from 1 January 1990 until 1 February 2000

In the relevant plot (Fig. 3), we observe that mostly the curve corresponding to the scale $i = 2000$ events lies in the highest level, the curve $i = 3000$ events in the middle and the curve $i = 4000$ events in the lowest level. There exists, however, the following interesting intersection: Around 8 March 1993 the curve $i = 3000$ events jumps to the highest level and remains so until 24 July 1994; subsequently the curve $i = 2000$ events returns to the highest level and after that a $M8.2$ EQ occurs on 4 October 1994 (cf., almost $2\frac{1}{2}$ months after the completion of the intersection between the scale $i = 3000$ events with that of $i = 2000$ events). This is an additional case where a major EQ happens after the detection of an intersection of Λ_i curves.

Discussion

An EQ of JMA magnitude $M = 7.6$ (USGS reported $M_w = 7.5$, see, e.g., <https://earthquake.usgs.gov/earthquake/eventpage/us6000m0xl>) with epicenter at $37.50^\circ\text{N } 137.27^\circ\text{E}$ occurred on the west coast of Japan on 1 January 2024, i.e., almost $3\frac{1}{2}$ weeks after drawing attention in Ref.⁴⁴ to the important fact focused on the phenomenon described in the last lines of the section describing the results from 15:00 LT on 11 March 2011 until now along with Fig. 4. Referring to the intersection mentioned there, i.e., the curve corresponding to the scale $i = 4000$ events (green) intersects the one for the scale $i = 3000$ (blue), the following comments are now in order: First, the two EQs of magnitude close to $M8$, i.e., the 2003 Tokachi EQ (see Fig. 1) and the 2015 Ogasawara EQ (see Fig. 2), have not been preceded by an intersection (see also Fig. 2 where the green curve approaches -but does not intersect- the blue curve). Second, concerning the $M8.2$ EQ in 1994 -exceeding the aforementioned two EQs of magnitude close to $M8$ - there exists an intersection, however, since the curve $i = 3000$ events in Fig. 3 jumps to the highest level and an intersection occurs with the curve $i = 2000$ events (red) around 8 March 1993. In other words, before 27 October 2022 the only intersection between the curves corresponding to the scales $i = 4000$ and $i = 3000$ events was observed before the Tohoku $M9$ EQ, see the section describing the Results from 1 January 1998 until the $M9$ Tohoku EQ on 11 March 2011. Thus the phenomenon emerged in Fig. 4 has only appeared before the Tohoku $M9$ EQ as can be visualized in the lower panel of Fig. 5—which is just an excerpt of Fig. 1—showing the following sequence before the Tohoku mainshock: (a) for several months (i.e., approximately 14.5 months from 25 October 2008 to 10 January 2010) the $i = 4000$ events curve slightly exceeded the $i = 3000$ curve (which actually occurred in the aforementioned 2023 case) and (b) subsequently the $i = 3000$ curve recovered for approximately 7 months (from 10 January 2010 to 5 August 2010). Then, a clear intersection occurs on around 5 August 2010 and the $i = 4000$ events curve starts to increase more rapidly until 22 December 2010 when a $M7.8$ EQ occurred. Almost two weeks later anomalous variations of the Earth's magnetic field mainly in the z-component appeared⁴⁵, which in reality reflects that an SES activity that accompanies this magnetic field^{15,16} also started (with a duration of around 10 days) and almost two months later the $M9$ Tohoku mainshock occurred. Notably Λ_{4000} exceeded by more than $0.02 \Lambda_{3000}$ at the time of occurrence of the $M9$ Tohoku EQ.

We also investigated the statistical significance of the phenomenon observed during this 219-day period (5 August 2010 to 11 March 2011) by randomly shuffling the EQ magnitudes from 1 January 1983 to 31 December 2023 and repeating the Λ_i calculations. We found that Λ_{4000} exceeded by more than $0.01 \Lambda_{3000}$ at the occurrence time of the $M9$ EQ being previously larger than Λ_{3000} for a period smaller than 219 days only in approximately 3% of the 500 synthetic catalogs investigated. Hence, the fact that Λ_{4000} exceeded Λ_{3000} 219 days before the $M9$ Tohoku EQ cannot be attributed to chance.

The aforementioned comments shed more light on why the phenomenon in 2023 -depicted in Figs. 4 and 5 (upper panel)- has been, followed very carefully as mentioned in Ref.⁴⁴ by comparing to the one that preceded the $M9$ Tohoku EQ. Furthermore, we note that a minimum $\beta_{W,min}$ of the order parameter fluctuations was found on 3 January 2024 as depicted in Fig. 6 (for the interpretation of these results see Ref.⁴⁶).

We now proceed to the estimation of the statistical significance of the observed phenomenon. As mentioned above on 8 March 1993, i.e., 19 months before the East-Off Hokaido $M8.2$ EQ on 4 October 1994, Λ_{3000} exceeded Λ_{2000} for the first time. A similar phenomenon concerning Λ_{4000} exceeding Λ_{3000} occurred on 14

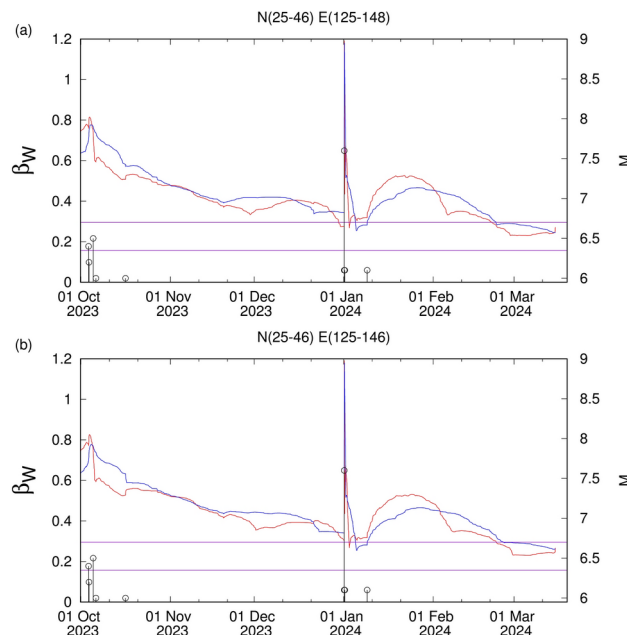


Figure 6. The variability β_W for $W = 200$ (red) and 300 (blue) versus the conventional time for (a) the area $N_{25}^{46} E_{125}^{148}$ and (b) the area $N_{25}^{46} E_{125}^{146}$ since 1 October 2023 until 16 March 2024.

June 2008, i.e., 32 months before the $M9$ Tohoku EQ on 11 March 2011, see the section describing the results from 1 January 1998 until the $M9$ Tohoku EQ on 11 March 2011. Thus, assuming that an alarm is set ON when such intersections occur, we find that for the time period from 1 January 1990 to 1 January 2022 consisting of 384 months the probability to have the alarm ON is $p_{ON} = (19 + 32)/384 = 13.28\%$. Obviously, the p -value to hit by chance both EQs of magnitude $M8.2$ or larger is $p = p_{ON}^2 = 1.76\%$, which points to statistical significance of the phenomenon observed. We clarify that the present calculation of the statistical significance does not include the period depicted in Fig. 4 because the intersection displayed after 1 January 2022 is still under investigation.

Here, we shed light on parameter selection and in particular about the physical reasons that led us to the selection of the scales $i = 2000, 3000,$ and 4000 events. We first recall that setting the threshold $M = 3.5$ to assure data completeness, we have 47,204 EQs in the study area $N_{25}^{46}E_{125}^{48}$ from 1984 to the time of occurrence of Tohoku EQ⁴⁰, which reflects that on the average around 150 EQs occur per month. Second, the fluctuations of the order parameter κ_1 of seismicity exhibit a minimum β_{min} when⁴⁷ an SES activity starts having a lead time ranging from a few weeks up to around $5\frac{1}{2}$ months (with an average value of around a few months or so)³. A detailed study⁴⁶ has shown that just before the initiation of the SES activity, the temporal correlations between EQ magnitudes exhibit an anticorrelated behavior⁴⁶ while after this initiation long range correlations prevail. In other words, a significant change in the temporal correlations between EQ magnitudes occurs when comparing the two periods before and just after the initiation of an SES activity. It is this important change that can be captured by the time evolution of ΔS_i and Λ_i . Note that the scale of $i \sim 1000$ events is of the order of the number of $M \geq 3.5$ seismic events that occur during a period around the maximum lead time of SES activities. Hence, in our present analysis, in order to first verify the recording of the minimum of β_{min} and the subsequent appearance of the initiation of the SES activity (so that to capture the aforementioned important change of EQ temporal correlations) one should use a scale exceeding the $i \sim 1000$ events.

A major EQ does *not* occur alone. In particular, it may be preceded by a foreshock as for example the case of the Tohoku $M9$ EQ in 2011 in which a $M7.3$ foreshock occurred almost 2 days before the mainshock, i.e., on 9 March 2011 at $143.28^\circ E$ $38.33^\circ N$. In addition, a major EQ is followed by aftershocks which usually obey the so called Bath law⁴⁸ according to which the magnitude difference between the mainshock and its largest aftershock is approximately 1.2. A few aftershocks may be also appreciably large EQs as for example the $M7.6$ EQ that occurred at 15:15 LT on 11 March 2011, i.e., almost half an hour later than the mainshock, and the $M7.3$ EQ at 17:18 LT on 7 December 2012 several months after the mainshock. Thus, in order to include in our analysis the aforementioned important change of the temporal correlations between EQ magnitudes associated with the preceding SES activities of both the relevant foreshocks and aftershocks, we should investigate the scales $i = 2000, 3000,$ and 4000 events.

We now comment on the uncertainties and limitations of the proposed approach as well as include potential sources of error and how they might affect the results. Returning to the important fact mentioned in the last paragraph of the results from 15:00 LT on 11 March 2011 until now, we recall that in Fig. 4 we used $M_c = 3.5$ as the cut-off magnitude which can ensure the EQ samples are complete during most of the time. Let us now investigate what happens if M_c will increase to $M_c = 4.0$ or to $M_c = 4.5$ shortly after $M7$ class EQs due to aftershock missing and study whether it will potentially affect the complexity measure. Such an M_c increase leads to the results depicted in Fig. 7a which extends from 1 January 2012 until 1 January 2024 upon the occurrence of the $M7.6$ EQ at the western coast of Japan. A careful inspection of this figure shows that, while in Fig. 4 (where $M_c = 3.5$) it is evident that from 27 October 2022 the curve corresponding to the scale $i = 4000$ events intersects the one for the scale $i = 3000$, here in Fig. 7a (where $M_c = 4.0$ resulting³⁵ in approximately 2.5 times smaller number of EQs and hence $i = 3000$ becomes $i = 1200$ and $i = 4000$ becomes $i = 1600$), such an intersection is delayed to 12 December 2022. In addition, in Fig. 7b (where $M_c = 4.5$ resulting in approximately 6.3 times smaller number of EQs and hence $i = 3000$ becomes $i = 476$ and $i = 4000$ becomes $i = 635$), an intersection can now be recognized on 15 January 2023; the curve corresponding to $i = 635$ exceeds the one corresponding to $i = 476$ and the latter recovers on 12 September 2023, see the dashed green arrows in Fig. 7. In other words, the M_c value may affect the complexity measure since we have seen that upon using $M_c = 3.5$ the evident intersection in Fig. 4 (see also Fig. 2) between the scale $i = 4000$ events with the scale $i = 3000$ events may be retarded (by almost three months), if we increase M_c .

In Fig. 8, we now present how our results are affected when elaborating the case of the $M8.2$ EQ that occurred in Japan on 4 October 1994 (Fig. 3). We consider two kinds of variation in Fig. 8a we increase/decrease i by 50 events while in Fig. 8b by 100. An inspection of this figure reveals that for the case of Fig. 8a the results remain unchanged while the situation becomes blurred for Fig. 8b. Hence, we conclude that a variation of i by up to ± 50 events definitely does not affect our proposed method.

A number of methods have appeared for EQ prediction as well as to prepare the population for a big EQ, e.g., see Ref.⁴⁹. For example, both seismic quiescence and seismic activation before large EQs have been repeatedly described in the scientific literature⁵⁰. Another example is an algorithm called $M9$ -MSc, which is based on premonitory seismicity patterns⁵¹. Furthermore, a promising technique is the so-called region-time-length (RTL) algorithm, which takes into account the epicenter, time, and magnitude of earthquakes, which is an effective technique in detecting seismic quiescence. In particular, Huang and Ding⁵² achieved to reduce the possible ambiguity due to the selection of model parameters in the algorithm and proposed an improved technique of searching for the optimal model parameters. The aforementioned methods are classified as long-term and mid-term EQ prediction methods according to Uyeda et al.²² while our efforts based on the discovery of SES and SES activities in 1980s and 1990s together the introduction of the natural time analysis in 2000s (including the present work) to short term EQ prediction methods.

The concept of “natural time” has analogies with the concept of “internal time” by Ilya Prigogine⁵³, but there exist also some differences as explained below: The gist of what Prigogine seems to have been after his decades of work seems to be captured in the following 1997 quote: “My colleague Paul Glansdorff and I have investigated the

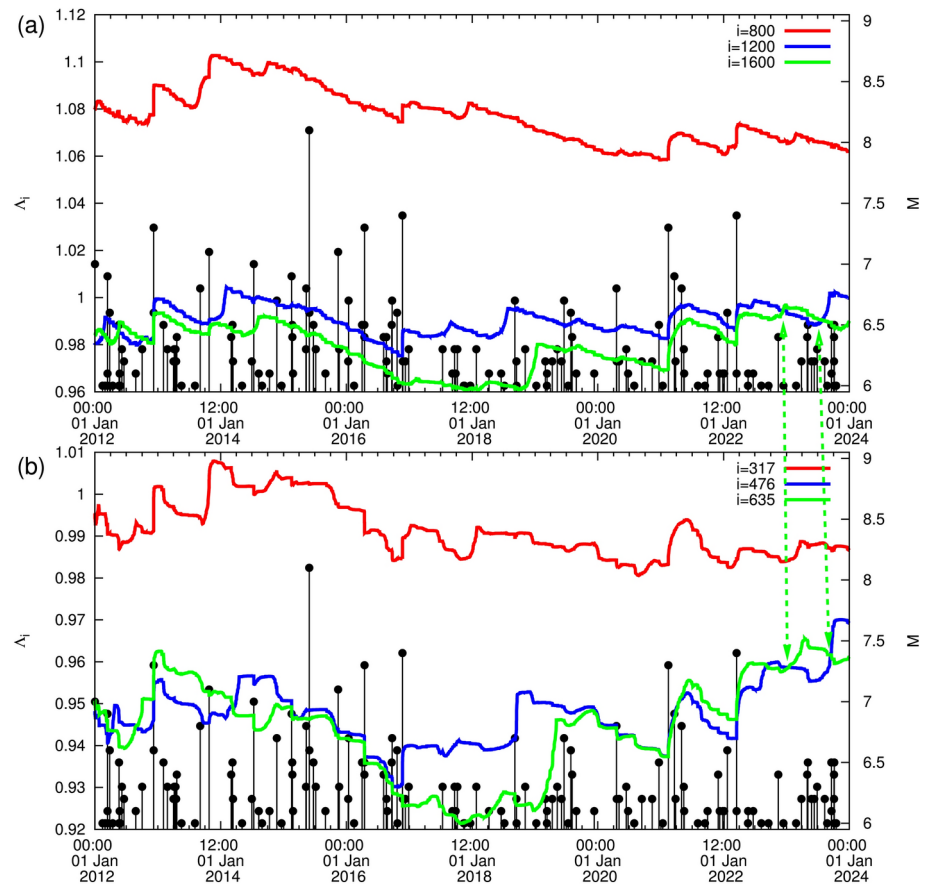


Figure 7. The complexity measure Λ_i for various scales when considering (a) $M_c = 4.0$ for $i = 800$ (red), 1200 (blue), and 1600 (green) and (b) $M_c = 4.5$ for $i = 317$ (red), $i = 476$ (blue), and 635 (green), versus the conventional time from 1 January 2012 until 1 January 2024. The green dashed arrows project the intersection observed for $M_c = 4.5$ to the results obtained for $M_c = 4.0$.

problem as to if the results of near-equilibrium can be extrapolated to those of a far-from-equilibrium situations and have arrived at a surprising conclusion: Contrary to what happens at equilibrium, or near equilibrium, systems far from equilibrium do not conform to any minimum principle that is valid for functions of free energy or entropy production.⁵⁴ (In place of free energy and entropy functions, Prigogine argues that matter acquires new properties when far from equilibrium in what fluctuations and bifurcations are the norm). On the other hand, in natural time analysis both the minimum ΔS_{min} and maximum of the fluctuations of ΔS appear far from equilibrium and in particular when approaching (i.e., a few months before) the EQ occurrence. For example, in the section Results from 1 January 1998 until the M9 Tohoku EQ occurrence on 11 March 2011 the following facts have been observed: a minimum of ΔS_{min} of the entropy change ΔS of seismicity in the entire Japanese region under time reversal was identified by Sarlis et al.³⁵ on 22 December 2010 together with a maximum of the fluctuations of ΔS ³⁰ (and hence of Λ_i).

Summary and conclusions

Studying the evolution of Λ_i curves, which quantify the fluctuations of the quantity $\Delta S \equiv S - S_-$, we obtain a procedure that identifies when the accumulation of stress occurs well before major EQs.

In particular, we find for the seismicity of Japan during the last 39 years for various scales i ($= 2000$ to 4000 events), that intersections of these curves occurred before the two strongest EQs (exceeding M8), i.e., the M9 Tohoku EQ on 11 March 2011 and the East-Off Hokaido M8.2 EQ on 4 October 1994. The same phenomenon is ascertained before the deadly Chiapas M8.2 EQ in 2017, which is Mexico's largest EQ in more than a century, as shown in Fig. 9. It is remarkable that all these 3 strong EQs (M9, 8.2 and 8.2) occur a few months or so after the completion of their preceding intersections which almost coincides with the lead time of SES activities, hence pointing to the physical mechanism proposed above for the phenomenon observed.

The physical meaning of the phenomenon of the intersection could be understood in the following context: As the system approaches destruction it becomes strongly non-equilibrium acquiring a scale invariant (e.g., multifractal) structure, thus the Λ_i values for different scales ($i = 2000, 3000, 4000$ events) may become very close hence the intersection occurs.

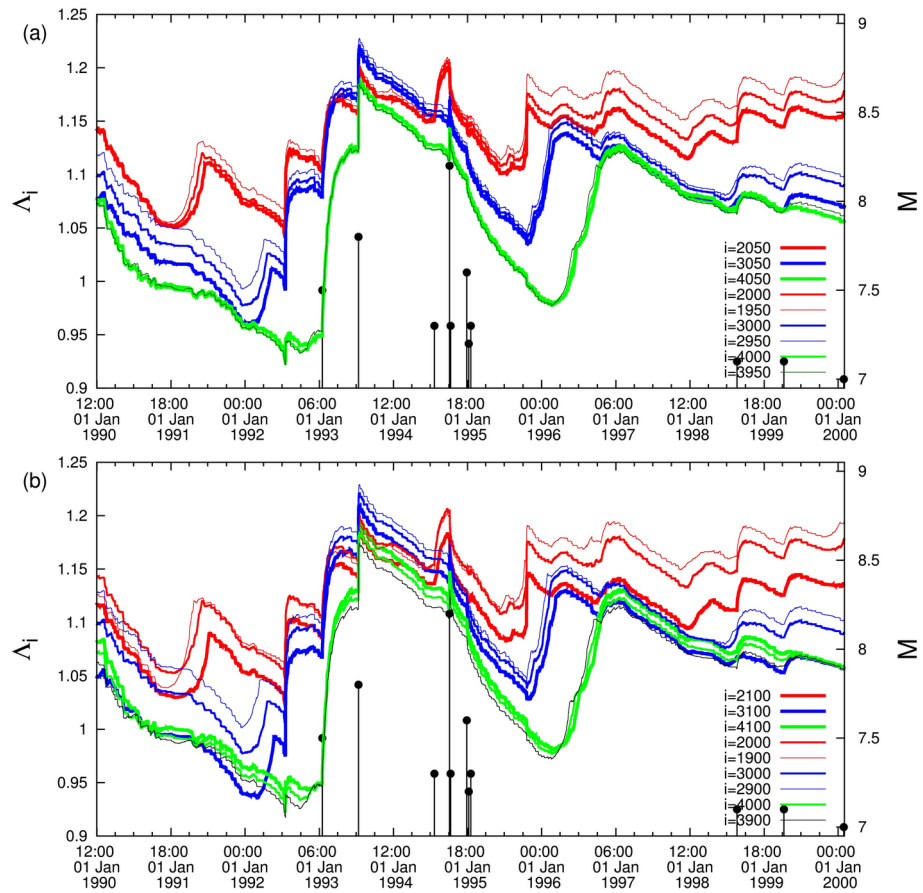


Figure 8. The complexity measure Δ_i for various scales i versus the conventional time from versus the conventional time from 1 January 1990 until 1 February 2000. Panel (a) corresponds to the case when we vary the scales $i = 2000$ (red), 3000 (blue), and 4000 (green) by 50 events, while (b) to the case of variation by 100 events.

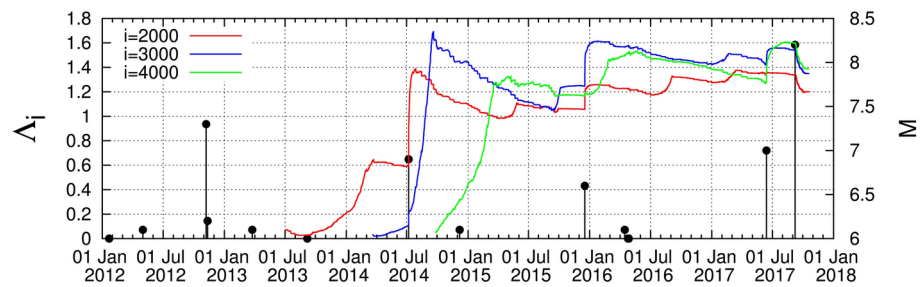


Figure 9. The complexity measure Δ_i for various scales $i = 2000$ (red), 3000 (blue), and 4000 (green) versus the conventional time from 1 January 2012 until the M8.2 Chiapas EQ in Mexico. Note that the curve corresponding to the scale $i = 4000$ exceeds the one of $i = 3000$ on 5 July 2017. For details on this calculation see Ref.³¹, see also Sect. 8.4 of Ref.²⁷.

Methods

The data used

We used the seismic catalog of the Japan Meteorological Agency (JMA) in a similar fashion as in Refs.^{40,43,55} by considering all EQs of magnitude $M \geq 3.5$ to assure data completeness from 1984 within the area $25^\circ - 46^\circ$ N, $125^\circ - 148^\circ$ E. The EQ energy was obtained from the JMA magnitude M by converting⁵⁶ to the moment magnitude M_w ⁵⁷. The Δ_i values were computed according to Eq. (4).

Natural time analysis: background

The motivation and the foundation of natural time analysis take into account the following two key points that have been considered by the first two authors as widely accepted when natural time analysis was proposed in 2001²⁶: First, the aspects on the energy of a system forwarded by Max Planck in his Treatise on Thermodynamics in 1945, and second, the theorem on the characteristic functions of probability distributions which Gauss called *Ein Schönes Theorem der Wahrscheinlichkeitsrechnung* (beautiful theorem of probability calculus)²⁷.

For a time series comprising N events, we define as natural time χ_k for the occurrence of the k -th event the quantity $\chi_k = k/N$ ^{23,26,58}. Hence, we ignore the time intervals between consecutive events, but preserve their order and energy Q_k . The evolution of the pair (χ_k, p_k) is studied, where $p_k = Q_k / \sum_{n=1}^N Q_n$ is the normalized energy for the k -th event. Using $\Phi(\omega) = \sum_{k=1}^N p_k \exp(i\omega\chi_k)$ as the characteristic function of p_k for all $\omega \in \mathcal{R}$, the behavior of $\Phi(\omega)$ is studied at $\omega \rightarrow 0$, because all the moments of the distribution of p_k can be estimated from the derivatives $d^m \Phi(\omega) / d\omega^m$ (for m positive integer) at $\omega \rightarrow 0$. A quantity κ_1 was defined from the Taylor expansion $\Pi(\omega) = |\Phi(\omega)|^2 = 1 - \kappa_1 \omega^2 + \kappa_2 \omega^4 + \dots$ where

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

A careful study shows⁵⁹ that κ_1 may be considered as an order parameter of seismicity and was also demonstrated⁵⁵ that the spatiotemporal variations of κ_1 reveal the epicenters of the EQs of magnitude $M \geq 7.6$. Considering a sliding natural time window of fixed length comprising W consecutive events, the variability β_W of κ_1 defined as $\beta_W = \sigma(\kappa_1) / \mu(\kappa_1)$ when for each EQ e_{i+1} in the seismic catalog^{40,60} we calculate the average value $\mu(\kappa_1)$ and the standard deviation $\sigma(\kappa_1)$, the κ_1 values resulting upon using the previous κ_1 for the EQs e_{i-W+1} to e_i . The fluctuations β_W of the order parameter of seismicity exhibit a minimum $\beta_{W,min}$ upon the initiation of an SES activity⁴⁷ upon using a sliding natural time window comprising the number of consecutive events that occur on average within a few months (which is the average lead time of SES activities before major EQs³).

The dynamic entropy S in natural time is given by²⁵

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

where $\langle f(\chi) \rangle = \sum_{k=1}^N p_k f(\chi_k)$ denotes the average value of $f(\chi)$ weighted by p_k , i.e., $\langle \chi \ln \chi \rangle = \sum_{k=1}^N p_k (k/N) \ln(k/N)$ and $\langle \chi \rangle = \sum_{k=1}^N p_k (k/N)$. Upon considering^{3,61} the time-reversal \hat{T} , i.e., $\hat{T}p_k = p_{N-k+1}$, the entropy obtained by Eq. (2), labelled by S_- , is given by

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

which is different from S . Hence, there exists a change $\Delta S \equiv S - S_-$ in natural time under time reversal, thus S being time-reversal asymmetric^{3,27,61,62}. The calculation of ΔS is carried out by means of a window of length i (=number of successive events), sliding each time by one event, through the whole time series, thus, a new time series comprising successive ΔS_i values is formed.

The complexity measure Λ_i quantifies the fluctuations of the entropy change ΔS_i under time reversal. It is defined by^{3,63}

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

where $\sigma(\Delta S_i)$ is the standard deviation of the time series of $\Delta S_i \equiv S_i - (S_-)_i$ and the denominator stands for the standard deviation $\sigma(\Delta S_{100})$ of the time series of ΔS_i of $i = 100$ events. In other words, it was shown that Λ_i quantifies how the statistics of ΔS_i time series varies upon changing the scale from 100 to another scale i . ΔS_i are of profound importance to study the dynamical evolution of a complex system (see p. 159 of Ref.³).

Data availability

The authors declare that the data supporting the findings of this study are available within the paper.

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Author contributions

P.A.V., N.V.S. and T.N. designed research, performed research, analysed the results, and reviewed the manuscript.

Declarations

Competing interests

The authors declare no competing interests.

Additional information

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