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Seismic quiescence as an indicator for large earthquakes in a system of self-organized criticality

Sebastian Hainzl, Gert Zöller, and Jürgen Kurths
Institute of Physics, University of Potsdam, Potsdam, Germany

Jochen Zschau
GeoForschungsZentrum, Potsdam, Germany

Abstract. Seismically active fault systems may be in a state of self-organized criticality (SOC). Investigations of simple SOC models have suggested that earthquakes might be inherently unpredictable. In this paper, we analyze the question of predictability in a more complex and realistic SOC model, which consists of a spring-block system with transient creep characteristics. Additionally to the power law distribution of earthquake sizes, this model reproduces also foreshock and aftershock sequences. Aside from a short-term increase of seismicity immediately prior to large model earthquakes, these events are preceded on average by an intermediate-term period of reduced seismicity. The stronger and the longer the duration of this period, the larger on average is the subsequent mainshock. We find that the detection of seismic quiescence can improve the time-independent hazard assessment. The improvement is most significant for the largest target events.

Introduction

For the last several years, a continuing debate has taken place on whether or not earthquakes are inherently unpredictable [*Geller et al.*, 1997; *Wyss,* 1997; *Nature debate,* 1999]. The statement of an inherent unpredictability is founded on the assumption that “the Earth is in a state of self-organized criticality, where any small earthquake has some probability of cascading into a large event” [*Geller et al.*, 1997]. In the concept of self-organized criticality (SOC), which was first introduced by *Bak et al.* [1987], a driven dissipative system with many degrees of freedom evolves spontaneously into a statistically stationary state characterized by power-law behavior of spatial and temporal correlation functions. Thus, a self-organized critical state of fault systems can explain the frequency-size distribution of earthquakes, that is, the Gutenberg–Richter law. Examples for earthquake models showing SOC, and therefore reproducing the Gutenberg–Richter law, are the models proposed by *Bak and Tang,* [1989], and by *Olami et al.,* [1992]. On the other hand, these models fail to reproduce some important properties of the spatiotemporal clustering of earthquakes observed in real fault systems. In particular, they do not show foreshock and aftershock sequences correlated to large earthquakes as well as earthquake swarms. It is questionable, to what extent simple SOC models, which exclude these fundamental features, can be used to draw reliable conclusions concerning the predictability of earthquakes.

The counterclaim to an inherent unpredictability is based on the observation of precursory phenomena. They are assumed to indicate a change of the system state [*Wyss,* 1997]. Foreshocks are the most obvious premonitory phenomenon preceding large earthquakes. In advance, however, foreshocks can be identified as such only with a low probability [*Ogata et al.,* 1996]. Aside from foreshocks, other precursory phenomena have been observed, e.g. ground water changes or electromagnetic emissions [*Wyss and Dmowska,* 1997]. In contrast to foreshocks, the statistical evidence for these observations is brought into question [*Geller et al.*, 1997]. This is valid also for the phenomenon of precursory seismic quiescence. A period of reduced earthquake activity is observed to last between months or years prior to many mainshocks. The duration is found to be the longer the larger the subsequent mainshock is [*Wyss and Habermann,* 1988]. Therefore, precursory seismic quiescence could be a promising candidate for intermediate-term predictions. However, its statistical significance is difficult to prove using seismicity catalogs, because the latter represent only a brief record of the system relative to the time scale of the seismic cycle.

In this paper, we try to bridge both the hypothesis of an underlying self-organized critical system state and the occurrence of precursory phenomena. Pre-existing hierarchical fault systems showing precursory phenomena have been already investigated with regard to the predictability of large events [*Huang et al.,* 1998]. Here, we analyze a recently proposed SOC model [*Hainzl et al.,* 1999] representing the class of homogeneous spring-block systems. This earthquake model reproduces in addition to the Gutenberg-Richter law several observed spatiotemporal characteristics of earthquakes, including foreshocks and precursory seismic quiescence. Although the synthetic earthquake catalogs contain much more information, in particular the spatial distribution of hypocenters as well as magnitudes, we restrict our analysis to the temporal variations of the seismic rate. The underlying question is to what extent fluctuations in the high-dimensional system state are reflected in such an easily observable quantity. In contrast to real earthquake catalogs, the predictability of large earthquakes can be checked in the numerically generated data with statistical significance.

Model

The model used here has been described elsewhere [*Hainzl et al.,* 1999]. Its basis is a cellular automaton version [*Olami*

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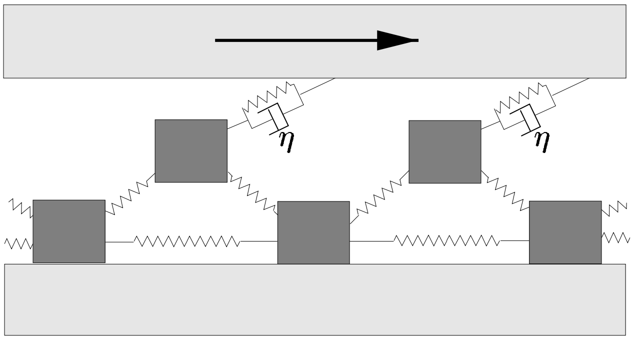

Figure 1. One-dimensional sketch of the investigated two-dimensional spring-block model. The bottom blocks, which perform stick-slip motion, are interconnected by springs. Additionally, they are coupled by further springs and dashpots (with viscous coefficient η) to the moving tectonic plate and frictionally to the lower plate. In the case of η=0, the model is equivalent to the model proposed by *Olami et al.* [1992].

et al., 1992] of the two-dimensional spring-block model originally proposed by *Burridge and Knopoff* [1967]. In extension to previous models, *Hainzl et al.* [1999] take into account in a first-order approximation transient creep characteristics observed in real fault systems [*Savage and Svarc,* 1997]. A one-dimensional sketch of the investigated two-dimensional block model is shown in Figure 1. The model parameters are (i) the elastic coupling constant between two adjacent blocks α, which can vary in the range of $0 \leq \alpha \leq 0.25$, (ii) the stress relaxation time T, which is proportional to the assumed viscous coefficient η of the material, (iii) the tectonic reloading time T_0, and (iv) the fraction of postseismically distributed stress $\kappa(1–4\alpha)$, where κ can vary between 0 and 1. However, block systems of this type evolve independently of the initial conditions into a statistically stationary state, which depends mainly on only two parameters, namely on α and T/T_0.

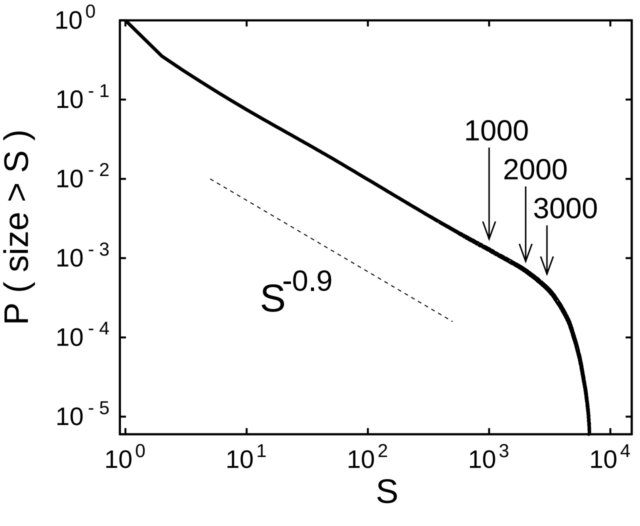

Figure 2. The probability density of observing an event of source size greater than S blocks as a function of S in the case of the analyzed model sequences. The dotted line corresponds to a B value of 0.9, whereas the arrows indicate the lower cutoffs for the mainshock definitions used in our investigations.

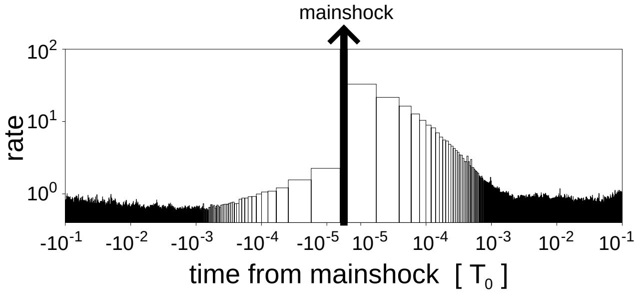

Figure 3. Log-log plot of the earthquake occurrence rate relative to the mainshock occurrence time. The curve shows the average of the seismic rate regarding 5000 mainshocks with size greater than 1000 blocks occurring in the analyzed model sequences.

In correspondence with the fully elastic model [*Olami et al.,* 1992], the model shows SOC. The self-organized state is characterized by a power law distribution of event sizes, limited only by the finite size of the block-system. The value of the power law exponent B increases, if α decreases. Figure 2 illustrates the size distribution for 100×100-block simulations with $\alpha = 0.2$. In this case the B value is within the range of empirically observed values, scattering around 1 [*Turcotte,* 1997].

In contrast to the fully elastic model, the visco-elastic model reproduces several observed spatiotemporal patterns of earthquakes: Large events are followed by aftershock sequences obeying the modified Omori law; and are preceded by localized foreshocks, which are initiated after a time period of seismic quiescence (see Figure 3). While a considerable variability of precursory seismicity is observed, the averaged earthquake activity, which is formed by stacking the records of seismic activity relative to the mainshock occurrence times, increases immediately prior to the mainshocks according to a power law. The exponent of the power law increase is identical to the Omori exponent p characterizing the power law decay of aftershocks. This is also known from empirical observations [*Jones and Molnar,* 1979]. The value of p depends on the normalized relaxation time T/T_0. Additionally, it is found in further agreement with real observations [*Suyehiro et al.,* 1964] that, compared with aftershocks, the distribution of foreshock sizes is characterized by a significantly smaller B value.

The analyzed synthetic catalogs (simulated with parameters α=0.2, κ=0.25 and T/T_0=10^{-4}) reproduce the empirically observed event size distribution ($B \approx 1$), the temporal clustering relative to mainshocks ($p \approx 1$), and additionally, swarm events, namely sequences of strongly clustered smaller events not associated with a mainshock. Large events themselves occur highly clustered, rather than periodic in time.

Predictability

In these synthetic catalogs, a short-term power law increase of seismic activity occurs immediately prior to the mainshocks on average. However, the precursory seismic patterns are found to vary largely for different mainshocks. Only in approximately half of the mainshocks, can correlated foreshocks be identified in retrospect. Furthermore, in the case of their occurrence, no obvious correlation between the size of foreshocks and the size of the mainshocks exists. This observation is in agreement with empirical findings [*Jones and Molnar,* 1979]. Thus it is not straightforward, maybe impossible, to identify foreshocks in advance; especially, a discrimination by means of the different size distribution of foreshocks, i.e. the smaller B value, is not feasible because of the small number of foreshocks.

However, in these simulations mainshocks are preceded on average by a further phenomenon, namely by a time interval of reduced seismic activity, which occurs prior to the foreshock activity. To illustrate this, we count the number of events preceding mainshocks in the time interval $T_0/10$. Here, a mainshock is defined as the largest event within its temporal vicinity $\pm T_0/10$. We find that the larger the mainshock is, the less events occur in this time interval (Figure 4a). Furthermore, one observes a transition in the seismic activity from a higher to a lower level. The onset of this relative seismic quiescence depends on the size of the following mainshock, namely the longer the duration of the seismic quiescence is, the larger is on average the subsequent mainshock (Figure 4b). This is in agreement with empirical observations [*Wyss and Habermann,* 1988]. The model mechanism for this dependence is simple. Due to the tectonic movement, the accumulated energy increases with the duration of seismic quiescence; that is, the probability for a large event also increases.

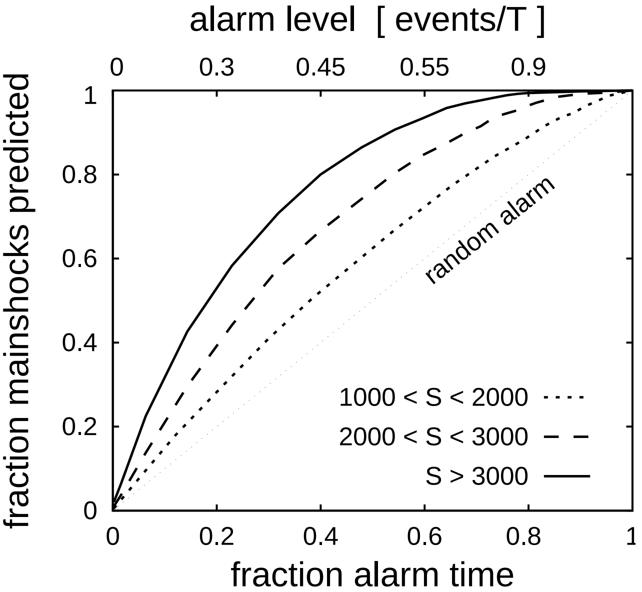

Figure 5. The success curve for predictions based on reduced seismic activity. An alarm is claimed or extended, if the seismic rate is below the alarm level.

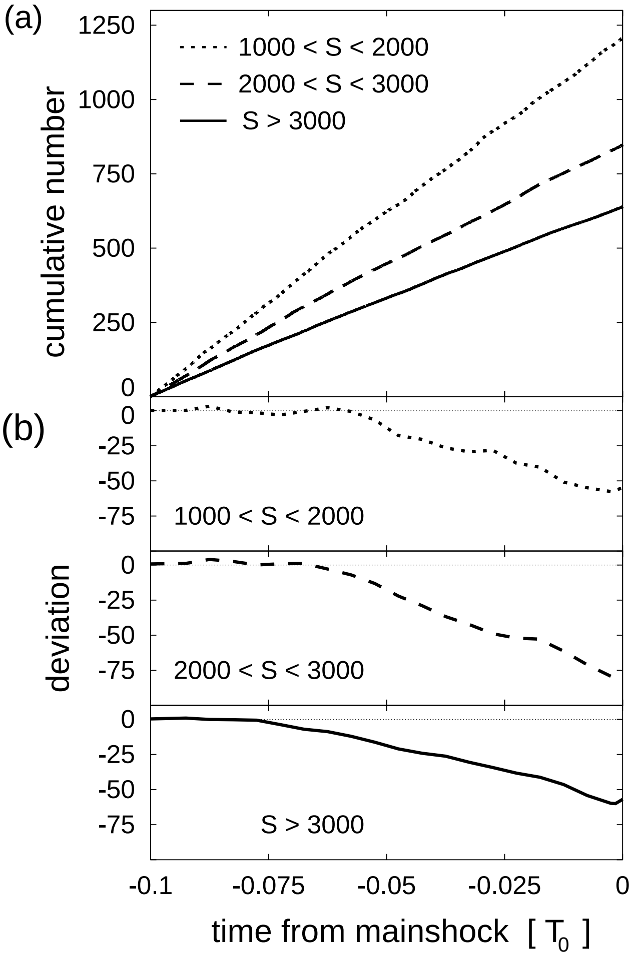

Figure 4. The time-dependence of the averaged seismic activity preceding mainshocks of different sizes: (a) the cumulative number of events prior to the mainshocks, and (b) the deviations from a linear increase. Each curve represents the average of the seismic rate regarding 1000 mainshocks of the noted size S.

In comparison to the duration of foreshock sequences, which is of the order of $10^{-4}T_0$, the duration of the seismic quiescence is much longer, namely of the order of $5\times10^{-2}T_0$. Thus, to identify such periods of quiescence, the seismic activity can be averaged over longer time intervals in order to smooth short-term fluctuations. To analyze the predictability of large events on the basis of seismic quiescence, we calculate the seismic rates in moving time windows of length $T_0/100$. Other window sizes do not change the results qualitatively. Alarm conditions are implemented in the way that alarm is announced or extended for the following time interval $T_0/100$, if the measured rate is below a certain threshold. The fraction of the total alarm time depends on the value of this threshold. We determine the fraction of large events predicted by alarms as a function of the threshold value, respectively the fraction of alarm time. This analysis is performed for simulations, which consist of several thousands of mainshocks, leading to statistically significant results. In Figure 5 the results are shown for mainshocks belonging to three different magnitude bands. We find that in all cases the number of predicted mainshocks exceeds the successful predictions for the case of randomly distributed alarms. Furthermore, the degree of predictability increases with increasing size of the target events. For example in the case of the largest events, approximately 50% of the targets are predicted when the alarm is on for 15% of the total time. Thus our investigations show that the time-independent hazard assessment can be improved by time-dependent estimations; that is, that large synthetic earthquakes are to a certain degree predictable.

Conclusions

Simple SOC models have been used as basis for the hypothesis of an inherent unpredictability of earthquakes, although these models fail to reproduce realistic spatiotemporal earthquake patterns. However, more complex models can reproduce some of these spatiotemporal characteristics [e.g. *Cowie et al.,* 1993; *Lyakhovsky et al.,* 1997]. With regard to predictability, we have analyzed a recently proposed SOC model [*Hainzl et al.,* 1999] showing in a realistic way clustering of earthquakes. In particular, two precursory signals known from real earthquake data are preceding large events in this model on average: an intermediate-term seismic quiescence and, immediately prior to the mainshocks, a short-term increase of seismic activity. The observed characteristics of both precursory phenomena, concerning the spatiotemporal patterns as well as the variation of the B value, are in good agreement with empirical findings. Thus, in comparison to previous investigations of SOC spring-block systems which lack realistic spatiotemporal dynamics [*Pepke and Carlson,* 1994], the analysis of this model seems to be more appropriate to judge the stated unpredictability of earthquakes.

It is difficult to identify the model foreshocks in advance. However we have found that the detection of epochs of reduced seismic activity can improve the hazard assessment for large earthquakes. In particular, the estimations are the better the larger the target events are. However, because of highly variable seismic activity prior to large earthquakes, the success ratio - that is, the factor of improvement in comparison to a time-independent estimation - is only of the order of three. On the other hand, it is behind the scope of our paper to optimize the prediction algorithms. Our investigations show that the self-organized state of a more realistic SOC earthquake model performs fluctuations correlated to the largest events. These variations are reflected to a certain degree in measurable quantities, even in simple measures such as event rates. In general, the degree of predictability seems to be determined by the amplitudes of these fluctuations, which are caused mainly by the energy dissipation due to earthquakes.

We have shown in accordance with results for hierarchical fault systems [*Huang et al.,* 1998; *Sornette,* 1999] that even for homogeneous fault systems the hypothesis of an underlying self-organized critical state does not lead automatically to an inherent unpredictability of earthquakes.

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S. Hainzl, J. Kurths, and G. Zöller, Institute of Physics, University of Potsdam, POB 601553, 14415 Potsdam, Germany. (hainzl@agnld.uni-potsdam.de)

J. Zschau, GeoForschungsZentrum, Telegrafenberg, 14473 Potsdam, Germany. (zschau@gfz-potsdam.de)

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