Using the Self-Organized Criticality Approach for Modeling Pre-Seismic Electromagnetic Emissions

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Abstract

We present a new approach to modeling electromagnetic emission signals generated in the Earth's crust prior to major earthquakes. The approach is based on a non-Abelian stochastic directed sandpile cellular automaton representing cooperative dynamics of rock cracks before and during the earthquake onset. When driven slowly, the automaton tends naturally to the state of self-organized criticality in which scale-free dynamics is observed in the form of power-law probability distributions of instability parameters as well as fractal geometry of seismic stress accumulation. Based on this model, we investigate numerically the possibility of using a fractal time-series analysis of pre-seismic electromagnetic emissions as a method for prediction of catastrophic seismic events.

Introduction

Regional seismicity is known to demonstrate scale-invariant properties in different ways. Some typical examples are fractal spatial distributions of hypocenters, Gutenberg-Richter magnitude statistics, fractal clustering of earthquake onset times, power-law decay of aftershock sequences, as well as scale-invariant geometry of fault systems. In certain regions, the observed scale-free effects are likely to be connected to a cooperative behavior of interacting tectonic plates and can be described in terms of the self-organized criticality (SOC) concept [*Bak et al.*, 1988; *Rundle et al.*, 2000]. In the present paper, we investigate a SOC model incorporating short-term fractal dynamics of seismic instabilities and slowly evolving matrix of cracks (faults) reflecting long-term history of preceding events. The model is based on a non-Abelian stochastic directed sandpile algorithm [*Hughes and Paczuski*, 2002] and displays a self-organizing fractal network of quasi-stable grid sites similar to the structure of stress field in seismic active regions. Using this algorithm, we consider two alternative mechanisms of the generation of pre-seismic ultra-low frequency (ULF) electromagnetic emissions [*Smirnova*, 1999] associated with conductivity fluctuations and moving charged dislocations [*Tzanis and Vallianatos*, 2002] in the Earth crust.

Method and results

The model is defined on a two-dimensional grid. Each grid site with coordinates x and y is prescribed the energy variable $z \in R$. The amount of energy stored in a given grid site (element) determines its ability to interact with its downstream nearest neighbors. If the condition $z>z_c$ is satisfied, the following interaction rules are applied:

$$
\begin{aligned}
z_{t+1}(x,y) &= z_t(x,y) - dz \\
z_{t+1}(x+1,y+1) &= z_t(x+1,y+1) + p\,dz \\
z_{t+1}(x,y+1) &= z_t(x,y+1) + (1-p)\,dz
\end{aligned} \tag{1}
$$

in which t is the discrete time and $p\in[0,\ 1]$ is the uniformly distributed random variable. After receiving a portion of energy from the excited element, one or two of its downstream neighbors can also become unstable producing a growing avalanche of activity which propagates along the y direction. The bottom boundary is open, the left and the right boundaries are subject to periodic boundary conditions. The model is driven by adding a small amount of energy to randomly chosen sites on the top row (x = 0). The choice d$z = z_t(x,y)$ makes the algorithm non-Abelian leading to the generation of non-trivial patterns of subcritical grid sites similar to fractal fault patterns in seismic active regions [*Hughes and Paczuski*, 2002].

It has been found [*Uritsky et al.*, 2004] that depending on the geometry of local stress distribution, some places on the model grid have higher probability of major instability events compared to the others. If observed in a real seismic system, such dependence could make фт evolving fractal pattern of faults a sensitive seismic risk indicator. In the model, one can associate different energy levels of grid elements with different values of Earth's crust electric conductivity. Assuming that stable (z = 0) and subcritical ($0 < z \le z_c$) grid sited symbolize respectively two different phases in the Earth crust, e.g. solid rocks and fluids filling up cracks in the rocks, with conductivity values being respectively 0 and 1, the average concentration of the conducting phase in spatial domain Ω is given by

$$
C(t) = \left\langle \theta\left(1 - z_t(x,y)\right) \right\rangle_{x,y\in\Omega} \tag{2}
$$

where θ is the Heaviside step function. One can also compute the percolation conductivity σ_p taking into account the connectivity of subcritical grid sites:

$$
\sigma_p(t) \quad = \left(\sum_{x\in\Omega} \left(\sum_{y\in\Omega} \left[Q(x,y) \times \theta\left(1 - z_t(x,y)\right) \right] \right)^{-1} \right)^{-1} \tag{3}
$$

Here, the factor Q equals 1 if a percolation cluster exists that connects left and right boundaries of Ω to which constant electric potential drop is applied, otherwise Q = 0.

Time evolution of $C(t)$ and $\sigma_p(t)$ signals reflects changes in model configuration due to SOC avalanches and is characterized by non-integer values of the coastline dimension. It has been suggested [*Uritsky et al.*, 2004] that fluctuations of the percolation conductivity defined above can be used for short-term prediction of the expected range of avalanche sizes, and represent a simple model of fractal precursor of major fault matrix reconfiguration due to strong earthquakes. Time derivatives of these signals (Fig. 1) are reminiscent of pre-seismic ULF electromagnetic emissions displaying characteristic clustering of activity spikes before major events [*Kopytenko et al.*, 1994].

Another method of building cellular automaton models of pre-seismic electromagnetic emissions can be based on the effect of moving charged dislocations (MCD) which was shown to accompany crack evolution before strong earthquakes [*Tzanis and Vallianatos*, 2002]. We considered each local instability (an excited element with ($z > z_c$) as a crack event associated with a transient electric dipole generating an electric field pulse. The superposition of such pulses from multiple simultaneous sources gives rise to a complex stochastic electromagnetic signal in ULF frequency band. By assuming that active cracks can only emit short-lived pulses with durations of few seconds, the overall shape of the electric field signal detected on the ground can be represented by the convolution of such pulses with the long-period source time function $n(t)$, where n is the time-dependent number of active grid sites. A typical source function and the resulting electric field fluctuations, which share a multiscale complexity of the $n(t)$ signal, are shown in Fig.2. The shape of the obtained emission signal seems to display some distinctive features (sudden onset, rapid culmination and slower decay) of MCD electromagnetic precursors predicted theoretically [*Tzanis and Vallianatos*, 2002].

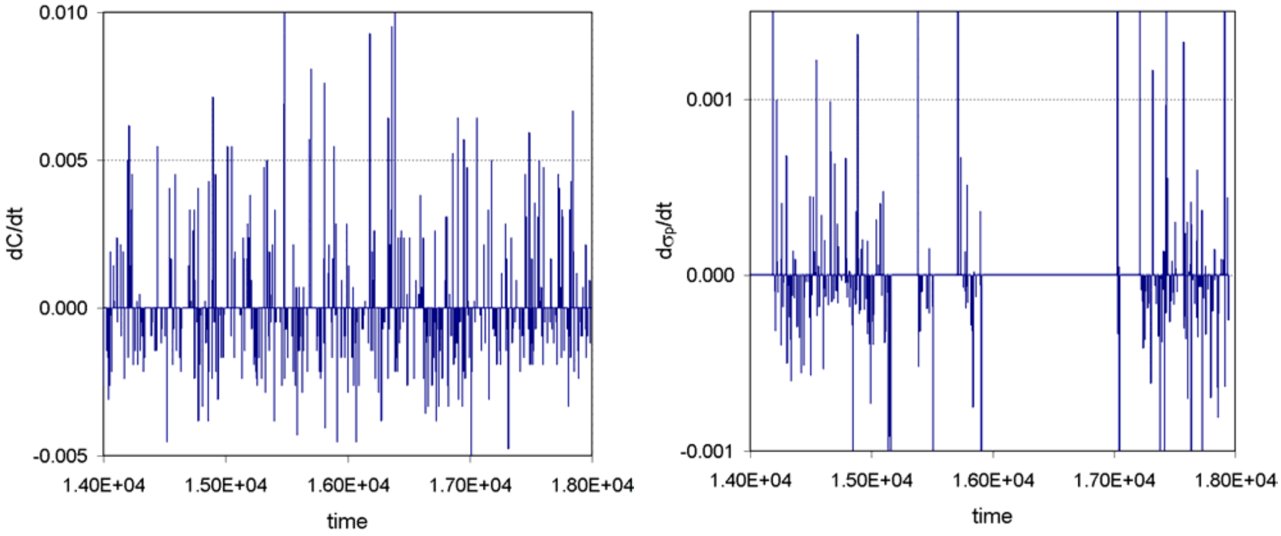

Fig. 1. Examples of time evolution of dC/dt and $d\sigma_p/dt$ conductivity signals in the stochastic directed sandpile model

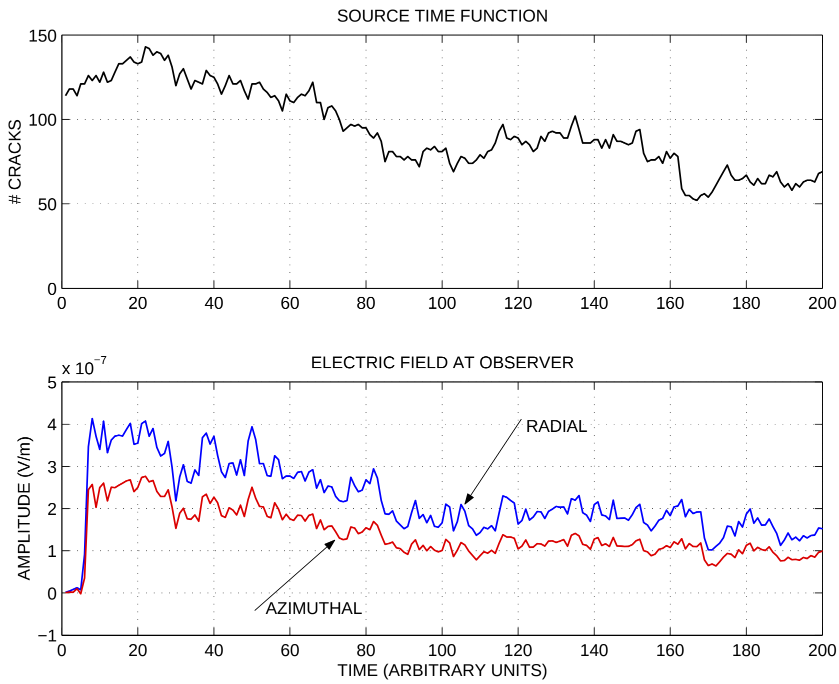

Fig. 2. Source function and MCD-generated electric field fluctuations produced by cooperative evolution of about 150 model avalanches

Conclusion

We have delineated two approaches to modeling pre-seismic stochastic electromagnetic signals based on a simple SOC model. Our simulations suggest that both conductivity and electric field fluctuations associated with local propagation of instability fronts can carry information on coupling effects between the evolution of fractal fault systems and the statistics of major earthquakes, which makes SOC a possible underlying mechanism of precursory nature of the ULF electromagnetic emissions.

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