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Small world picture of worldwide seismic events

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HIGHLIGHTS

- Pioneer earthquake study for the whole world.
- Connectivity distributions are power laws with exponential cutoff.
- Small-world properties found for the Earth's seismic network.
- The inter event intervals distribution is a Tsallis' one.

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ABSTRACT

The understanding of long-distance relations between seismic activities has for long been of interest to seismologists and geologists. In this paper we have used data from the worldwide earthquake catalog for the period between 1972 and 2011 to generate a network of sites around the world for earthquakes with magnitude $m \geq 4.5$ in the Richter scale. After the network construction, we have analyzed the results under two viewpoints. First, in contrast to previous works, which have considered just small areas, we showed that the best fitting for networks of seismic events is not a pure power law, but a power law with exponential cutoff; we also have found that the global network presents small-world properties. Second, we have found that the time intervals between successive earthquakes have a cumulative probability distribution well fitted by nontraditional functional forms. The implications of our results are significant because they seem to indicate that seisms around the world are not independent. In this paper we provide evidence to support this argument.

1. Introduction

The general belief in seismic theory is that the relationship between events that are located far apart is hard to be understood/demonstrated. However we live today in a world where data is being collected on most aspects of our lives and better yet, computer power is cheaply available for analyzing such data. When we apply the computer power to the data we open a series of possibilities to look for patterns in the data. The work on seismic data analysis is no different; we have now large collections of millions of seismic events from around the world each deserving deeper analysis. In this paper we have found some evidence that points to small-world characteristics in the existing data on seismic events. An event in

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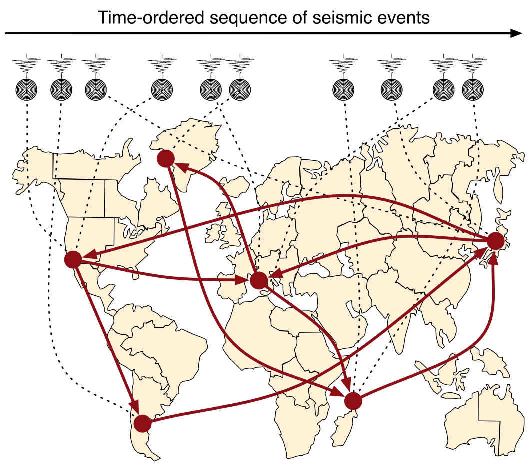

Fig. 1. A sketch of how the network of seismic events is created. At the top of the figure we see a sequence of time-ordered seismic events. Since each event has an epicenter E with location (θ_E, ϕ_E) we can use Eq. (10) to calculate which cell in the map to be used as a node in the network. The nodes are linked based on the sequence of events shown at the top of the picture.

a particular geographical site appears to be related to many other sites around the world and not only to other events at nearby sites.

The ability to find useful information from data is not new and is commonly known as Data Mining. However, since the work from Barabási and Albert [1] researchers have turned their attention not to mining the data itself but rather organizing the data in a network which captures relationships between pieces of data and only then mining the network structure and hence the relations between pieces of data. The network may review patterns that could not be observed from mining the raw pieces of data. The use of networks as a framework for the understanding of natural phenomena is nowadays called *Network Science*.

In the last few years, some analysis related to seismic phenomena demonstrated that earthquakes display features explained from the perspective of non-extensive statistical mechanics [2–6]. These networks display complex features that can be better understood statistically using the Tsallis entropy [7]. Through the analysis of distances and time intervals between successive earthquakes using non-extensive statistical mechanics, the authors have found that two successive earthquakes are indivisibly correlated, no matter how much spatially far they are from each other [8].

In line with the successive earthquake model mentioned above, recent studies [9,10] have applied concepts of complex networks to study the relationship between seismic events. In these studies, networks of geographical sites are constructed by choosing a region of the world (e.g. Iran, California) and its respective earthquake catalog. The region is then divided into small cubic cells, where a cell will become a node of the network if an earthquake occurred therein. Two different cells will be connected by a directed edge when two successive earthquakes occurred in these respective cells. If two earthquakes occur in the same cell we have a loop, i.e., the cell is connected to itself. Fig. 1 depicts a toy example of a network being formed. This method of describing the complexity of seismic phenomena has found that, at least for some regions, the common features of complex networks (e.g. scale-free, small-world) are present. However, in spite of the importance of the results, they are somewhat expected, since it makes sense for areas located geographically near to each other to be correlated.

In this paper we have used data from the worldwide earthquake catalog for the period between 1972 and 2011, to generate a network of sites around the world. Since only seismic events with $m \geq 4.5$ are recorded for all locations around the world, we then consider them *significant events* and used this set in our analysis (all seisms with 4.5 or more on the Richter scale). The results were analyzed under two viewpoints. The first, under the perspective of complex network theories, and the second using non-extensive statistical mechanics.

2. Theoretical background

2.1. Complex networks' features

Scale-free networks are defined as those in which the degree distribution of nodes (or vertices) follows a power law, that is, the probability that a network will have nodes of degree k, denoted by $P(k)$ is given by

$$P(k) \sim k^{-\gamma}, \tag{1}$$

where γ is a positive constant.

Eq. (1) states that scale-free networks have a very small number of highly connected nodes (called hubs) and a large number of nodes with low connectivity. These networks exist in contrast with general random networks with a very large