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Order parameter analysis of seismicity of the Mexican Pacific coast

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ABSTRACT

The natural time domain has shown to be an important tool to obtain relevant information hidden in time series of complex systems not easily obtainable by means of standard analysis methods. By assuming that tectonism is a complex system and that earthquakes are similar to a phase transition, it is possible to define an order parameter for seismicity in the context of the natural time domain. In this work we analyze the statistical features of the order parameter (OP) computed for the seismic Mexican catalog spanning from 1974 to 2012. We found that in four out of the six regions the *pdf* of the order parameter fluctuations is similar with that earlier reported by other authors, but in two of these regions noticeable differences are identified. Also, except for Michoacán, the scaled pdfs analysis of all regions collapse on a universal curve with non-Gaussian tails.

1. Introduction

Varotsos et al. [1] introduced the natural time domain (NTD) analysis, as a tool to analyze features in geoelectric time series like the so-called Seismo Electric Signals (SES). An advanced and extensive description of this methodology can be found in Ref. [2, and references therein]. The main principle of this method considers the time (see Section 3) as an index of the occurrence of the k-th event in a time series of N events. Under this frame, dynamical features hidden behind the time series in complex systems can emerge and this enables the study of the dynamical evolution of a complex system and identifies when the system enters a critical stage. Some applications [3–6] of this methodology have given important results that other tools cannot display [7]. The variance and entropy, defined in natural time domain, are able to distinguish and characterize different signals like seismic electric signals, "artificial" noises, and electrocardiograms by recognizing the non-Markovianity in all these signals. For instance in Refs. [8,9] NTD studied the statistical properties of the order parameter for seismicity in natural time, of the California and Centennial seismic catalogs and, in Ref. [10], a characterization of a chaotic map and SES observed in geoelectric time series associated with a earthquake occurring in Mexico was reported.

It is well known that the tectonic systems are complex systems at a critical point [8] characterized by scaling spatial and temporal complex correlations of the earthquake occurrences; it was also proposed that the earthquakes are equivalent to a phase transition [11]; therefore, an order parameter (OP) must be introduced to characterize the system in a critical state considering that the OP fluctuations display non-Gaussian distributions, characterize the onset of order at the phase transition and usually diverge approaching to the critical point [2].

On the other hand, in Refs. [12–14] analyzing the spatio-temporal distribution of earthquakes by studying the recurrence time inter-events, it was found that such distributions are not Poissonian but indicate some kind of correlation. In particular;

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several investigation have shown the existence of clustering effects in the time distributions of earthquakes, leading to the presence of time correlations in seismic sequences [15,16]. Furthermore, in Ref. [17] it was found that earthquake networks follow a universal scaling behavior.

The natural time χ, introduced in Ref. [1], is a methodology that considers time as a discrete variable, and the earthquakes are described as a sequential order of the occurrence of quakes where the elapsed time between pairs of earthquakes is not relevant. The natural time analysis discloses dynamical features hidden in the time series, allowing to study the dynamical evolution of a complex system and to identify when the system enters a critical state [2].

In the context of NTD, for seismicity [8] proposed in the natural time domain that the order parameter of seismicity is the normalized power spectrum $\Pi(\omega)$ ($\omega \to 0$) or the variance κ_1. The probability distribution function $P(\Pi(\omega))$ and the scaled $\sigma P(\Pi(\omega))$ vs. $(\Pi(\omega) - \langle\Pi(\omega)\rangle)/\sigma$ of the OP fluctuations were used to investigate the properties of seismicity [2]. It was reported in Refs. [2,8] that the order parameter fluctuations – relative to the standard deviation of the scaled distributions of different seismic areas (as well as that of the worldwide seismicity) – fall on a universal curve and this curve that exhibits an "exponential tail" similar to that observed in certain non-equilibrium systems (3D turbulent flow) as well as in several equilibrium critical phenomena, (2D, 3D Ising, *XY* models). Varotsos et al. [18,6] characterized the statistical behavior of some seismic regions by studying the probability density function of order parameter in the NTD for several seismic catalogs (Southern California Earthquake, Japanese, Greek, among others), but they did not consider the role of the tectonic characteristics of the studied regions.

The seismicity in the Mexico and Central America region is characterized by an active seismic belt along the Middle America Trench that has been extensively studied [19–24]. In the present work we perform the NTD analysis for the subduction and dispersion tectonic regions of the Mexican Pacific coast (Baja California (BC), Jalisco–Colima (J), Michoacán (M), Guerrero (G), Oaxaca (O), and Chiapas (CH)). The aim of this work is to study the *probability density function* (*pdf*) of $P(\kappa_1)$ and $\sigma P(\kappa_1)$, where σ is the standard deviation in NTD of the order parameter fluctuations (κ_1), for each of the above seismic regions. The geometry and the geodynamics are associated with tectonic factors, so it is possible that the local seismicity could be correlated with those features.

2. Tectonic regions

To characterize the seismicity of Mexico produced by the tectonic movements in the Pacific edge, we proposed to investigate the order parameter fluctuations in a dispersion zone and five other zones with subduction mechanism. Span and subduction are often assumed to be perpendicular to the strike of a ridge or trench, but oblique motion is also possible, as in transform faults, such as the Pacific–North America plate boundary in southernmost California and Baja California that includes the major plate boundary faults; these faults connect in a complex geometrical pattern, with either large or small scales, and after it continued into a divergent tectonic plate boundary, the East Pacific Rise in the Gulf of California.

The Mexican subduction regions were described in Refs. [20,21,24], where a complete study that takes into account the geometry of the subducted Rivera and Cocos plates beneath the North American lithosphere was reported, and some lags of seismicity were also identified. On the basis of these studies, southern Mexico may be segmented into five regions: (J) the Jalisco–Colima region to the west, where the Rivera plate subducts at a steep angle that resembles the geometry of the Cocos plate beneath the Caribbean plate in Central America; (M) the Michoacán region, where the dip angle of the Cocos plate decreases gradually toward the southeast; (G) the Guerrero region bounded approximately by the onshore projection of the Orozco and O'Gorman fracture zones, where the subducted slab is almost sub horizontal and under plates the upper continental plate for about 250 km, (O) the Oaxaca and (CH) Chiapas region in southeastern Mexico, where the dip of the subduction gradually increases to a steeper subduction in Central America.

More recently, in Refs. [25,26], a seismo-tectonic division of Mexico into 19 regions taking into account seismic characteristics of the existing catalogs for the seismicity occurring in Mexico from 1899 to 2007 was made. They made a seismic historic compilation from previous publications and of some catalogs: [20,27–31], International Seismology Center (ISC), USA Geological Service, the National Oceanic and Atmospheric Administration's (NOAA) of USA, the National Seismological Service (SSN; Servicio Sismológico Nacional, UNAM) and the Seismic northwest web of Mexico (RESNOM; Red Sísmica del Noroeste de México). The criteria used to cluster in regions the seismicity were: (i) similar characteristics of hypocenter localization, (ii) common tectonic characteristics, (iii) similar fault pattern or focal mechanism, (iv) main features of seismic energy release in each region, (v) local history of the mainshocks and (vi) to have the minimum number of primary regions. The main hypotheses in their regionalization are the differences in the estimation of local *a*- and *b*-values in the Gutenberg–Richter approximation and also the estimations from the same parameters of the local recurrence time T_L, for the same regions. Almost twelve regions are out of the zones of interest in this study, the other 7 regions of their study are comprised in the six selected regions of the present study and are quite coincident (Fig. 1). These six regions were named as the political state name and the areas were adjusted following the above-mentioned studies.

3. Natural time domain analysis

The NTD was introduced by Varotsos [1], and could be shortly described as follows: in a time series of N events the natural time $\chi_k = k/N$ can be viewed as an index of occurrence of the k-th event [1,32]. In natural time, the pair (χ_k, Q_k) is analyzed, where Q_k denotes in general a quantity proportional to the energy associated with the k-th event; for the seismicity Q_k is the