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Morisita-based space-clustering analysis of Swiss seismicity

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HIGHLIGHTS

- The *m*-Morisita index analysis was applied to the Swiss seismicity.
- The whole catalog is more spatially clusterized than the aftershock-depleted one.
- The spatial clustering increases with the increase of the threshold magnitude.
- The whole and aftershock-depleted catalogs show similar multifractal behavior.

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ABSTRACT

The *m*-Morisita index analysis was applied to the Swiss seismicity to investigate its space clustering properties. The analysis of the whole and aftershock depleted catalogs has revealed that the whole catalog is more spatially clusterized than the depleted one and that the clustering increases with the increase of the threshold magnitude. Furthermore, the multifractality degree of both catalogs is approximately the same. Our findings evidence the role played by the aftershocks in contributing to the increase of the spatial clustering of the earthquakes and that the spatial heterogeneity of seismicity is controlled by the main faults that produce the most independent events.

1. Introduction

Earthquake clustering represents an important issue in the context of studies devoted to the dynamical characterization of seismicity in spatial, temporal and magnitude domains [1–5]. The concept of clustering can be considered like a unifying idea of the large variety of space–time structures and patterns of seismicity, in the sense that it identifies deviations from a time-stationary and/or space-inhomogeneous Poisson process marked by the magnitude of the events. Therefore, the investigation of temporal and spatial clustering properties of earthquake sequences has been one of the most crucial features in seismicity analysis, because of its implications in terms of the geodynamical characterization of the seismic process [6–12].

Clustering represents also the main idea behind all the methods that have been developed for the aftershock removal, linking the concept of clustering to that of space–time correlation of a mainshock with the following earthquakes [13–19].

Focusing on space domain, even if spatial clustering is a more pronounced phenomenon that involves earthquakes concentrated along the boundaries of major tectonic plates (e.g., Refs. [20,9]), nevertheless, also at a regional (and so, smaller) level the spatial clustering is observed in seismotectonic areas, which are, of course, characterized by a regional fault network. For instance, De Rubeis et al. [6] used the fractal method based on the correlation integral to study the temporal changes in the 2-D distribution of earthquakes in three seismic zones of Italy, finding significant variability well correlated

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with the major events and clearly marking the beginning and the end of an earthquake cycle. Lapenna et al. [21] characterized the space clustering of a seismically active area of southern Italy by using the fractal dimension and found that it decreases with the increase of the threshold magnitude. Telesca et al. [22] recognized the presence of a strong space clustering associated with the major events. Very recently, Rotondi and Varini [23] identified space clustering in the eight tectonically homogeneous macro-regions in which the Italian territory has been divided, considering the events with relatively large magnitude (larger or equal to 4.5); such space clustering tends to drastically decrease or disappear with the increase of the threshold magnitude.

The space clustering of earthquake epicenters, generally quantified by the fractal correlation dimension, has been put in close relationship with the seismological parameter obtained by the Gutenberg–Richter law, the *b*-value that represents the power-law exponent of the magnitude distribution. It was found that there is an inverse relationship between *b* and the stress distribution [24]: low *b* value is associated with higher magnitude, high *b* value with lower magnitudes. In spatial analysis a low *b* value indicates that the stress regime grows until larger magnitude earthquakes are unleashed; while high *b* value reveals a low stress buildup with a stress release continuing through time with numerous smaller-magnitude earthquakes [25–29]. In this sense, the *b*-value can be considered as an indicator of the heterogeneity of the medium [30–32,28]. The fractal correlation dimension is used to describe the spatial pattern of an earthquake sequence, within a specific range of spatial scales from the limits of saturation (large scales) to those of depopulation (small scales). A lower correlation dimension reveals higher space clustering while a higher value depicts uniform or random spatial distribution; thus, it quantifies the degree of crustal deformation space [33]. So, both the *b*-value and the correlation dimension are indicators of the degree of clustering spatial characteristics of seismicity. Nevertheless, the relationship is not unique. A positive correlation between fractal dimension and *b*-value was suggested by Aki [34] and later supported by other authors analyzing different seismo-tectonic settings (e.g. Refs. [35,33,36–38,32,39,40]). However, other studies have highlighted the negative correlation between these two variables; for instance, Bayrak and Bayrak [41] found negative correlation between the *b*-value and the correlation dimension for several seismic zones in Western Anatolia.

In this paper, we will analyze the spatial properties of the seismicity in Switzerland and surrounding areas from 2001 to 2012 using a novel version of the multipoint Morisita index introduced in Ref. [42]. This index has revealed its potential to detect structures in spatial patterns, and it was shown to be related to Rényi's generalized dimensions.

2. Data

We analyzed the seismicity data of the Swiss territory and adjacent areas. The data were extracted from the ECOS-09 Catalog (SED Catalog) that can be downloaded from the website of the Swiss Seismologic Service (http://hitseddb.ethz.ch:8080/ecos09/introduction.html). Even though the catalog spans from 250 A.D. until 31 August 2008, we have analyzed the seismic catalog since 27 August 2001; on this date, the event detection was switched from the old short-period network to the new broad-band network, thus increasing the sensitivity at higher frequencies and decreasing the magnitude detection threshold of the network (ECOS-09, 2011). A further pre-processing was performed, removing from the catalog all the events classified as "uncertain", those recorded without the specification of the magnitude and all those events classified as "induced". The remaining catalog contains 5666 events with magnitude ranging from 0.88 to 5 and depth until 47 km. Fig. 1 shows the spatial distribution of the investigated seismicity. According to Woessner and Wiemer [43], we analyzed the cumulative and the non-cumulative frequency–magnitude distributions and estimated the completeness magnitude by the maximum curvature method, obtaining the completeness magnitude $M_C = 1.6$ (Fig. 2). The *b*-value of the Gutenberg–Richter law, calculated with the maximum likelihood method [44], is 1.08, which is in agreement with that obtained for many seismic areas worldwide.

3. The multipoint Morisita index

The multipoint Morisita index [42,45] is based on a grid of Q cells of changing size δ. The grid is superimposed on the points of the studied data set and the index measures how many times more likely it is to randomly select m ($m \geq 2$) points belonging to the same cell than in the case of a random distribution generated from a Poisson process. Mathematically, the index is computed as follows:

$$I_{m,\delta} = Q^{m-1} \frac{\sum_{i=1}^{Q} n_i(n_i-1)(n_i-2)\cdots(n_i-m+1)}{N(N-1)(N-2)\cdots(N-m+1)} \tag{1}$$

where n_i is the number of points falling in the ith cells and N is the total amount of points in the data set. The algorithm starts with a relatively high cell size δ and is iterated for decreasing δ until a minimum value is reached. For a given value of m, it is then possible to draw a plot relating each $I_{m,\delta}$ to its matching δ. If the studied point distribution has been generated from a Poisson process, $I_{m,\delta}$ fluctuates around 1; if the points are dispersed (i.e. repel one another), $I_{m,\delta}$ decreases to zero as δ is reduced and, if the points are clustered, the empty cells at small scales increase the value of $I_{m,\delta}$. It has been shown that the multipoint Morisita index becomes more sensitive to the characteristics of a set as m increases. Besides, for fractal patterns and under certain conditions, it is related [42] to Rényi's generalized dimensions D_q, for $q = m$, through the following power law:

$$I_{m,\delta} \propto \delta^{(m-1)(D_m-E)} \tag{2}$$