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Seismic clusters analysis in Northeastern Italy by the nearest-neighbor approach

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ABSTRACT

The main features of earthquake clusters in Northeastern Italy are explored, with the aim to get new insights on local scale patterns of seismicity in the area. The study is based on a systematic analysis of robustly and uniformly detected seismic clusters, which are identified by a statistical method, based on *nearest-neighbor* distances of events in the space-time-energy domain. The method permits us to highlight and investigate the internal structure of earthquake sequences, and to differentiate the spatial properties of seismicity according to the different topological features of the clusters structure.

To analyze seismicity of Northeastern Italy, we use information from local OGS bulletins, compiled at the National Institute of Oceanography and Experimental Geophysics since 1977. A preliminary reappraisal of the earthquake bulletins is carried out and the area of sufficient completeness is outlined. Various techniques are considered to estimate the scaling parameters that characterize earthquakes occurrence in the region, namely the *b*-value and the fractal dimension of epicenters distribution, required for the application of the nearest-neighbor technique. Specifically, average robust estimates of the parameters of the Unified Scaling Law for Earthquakes, USLE, are assessed for the whole outlined region and are used to compute the nearest-neighbor distances.

Clusters identification by the nearest-neighbor method turn out quite reliable and robust with respect to the minimum magnitude cutoff of the input catalog; the identified clusters are well consistent with those obtained from manual aftershocks identification of selected sequences. We demonstrate that the earthquake clusters have distinct preferred geographic locations, and we identify two areas that differ substantially in the examined clustering properties. Specifically, *burst-like* sequences are associated with the north-western part and *swarm-like* sequences with the south-eastern part of the study region. The territorial heterogeneity of earthquakes clustering is in good agreement with spatial variability of scaling parameters identified by the USLE. In particular, the fractal dimension is higher to the west (about 1.2–1.4), suggesting a spatially more distributed seismicity, compared to the eastern parte of the investigated territory, where fractal dimension is very low (about 0.8–1.0).

1. Introduction

The Friuli Venezia Giulia Region (FVG, Northeastern Italy) and surrounding areas experienced at least eight historical destructive earthquakes since 1348, the most recent one being the 1976 May 6 M6.4 earthquake, located in the Julian Prealps (Rovida et al., 2011). The identification and statistical characterization of seismic clusters may provide new insights about the features of seismic energy release and their relation to physical properties of the crust within the FVG region and surrounding areas (Gentili and Bressan, 2008; Peresan et al., 2015). A rigorous quantitative analysis of earthquakes occurrence is also useful to properly frame the sequences of moderate size events that occasionally, yet steadily, hit this region, an area characterized by high seismic hazard, but where only low-to-moderate magnitude events have been recorded during the last decades. Thus, this study will serve the dual purpose of developing better tools for mitigating impact from possible damaging earthquake sequences, as well as for providing a quantitative basis to understand the role of moderate size earthquakes in the framework of regional seismicity.

Significant steps have been made towards assessing earthquake clustering, space-time correlations and the emergence of seismicity patterns (e.g. Sobolev, 2011; Tiampo and Shcherbakov, 2012; Radan et al., 2013; Peresan, 2017). The observed seismic dynamics before and after many major earthquakes, demonstrated common features of predictability and diverse behavior (Keilis-Borok and Soloviev, 2003), both at national (Peresan et al., 2005; Gentili, 2010; Gentili and Di Giovambattista, 2017; Gentili et al., 2017; Peresan, 2017) and regional scale (Gentili and Bressan, 2007; Peresan et al., 2011). Seismicity,

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however, is just one possible expression of Earth's complex dynamics. A variety of physical data, ranging from ground-related deformation patterns (e.g. satellite observations from Global Positioning System, GPS) to tomographic, thermal and rheological properties, are available nowadays to characterize stress variations in the lithosphere, which can be eventually correlated with the identified seismicity patterns (Riguzzi et al., 2012; Panza et al., 2013; Bressan et al., 2016; Panza et al., 2017).

This study aims to provide a systematic identification of seismic sequences (including swarms) and to highlight possible regularities in the clustering features of recent seismicity in the FVG region, expanding observations about selected clusters analyzed in earlier studies (Gentili and Bressan, 2008). The study of the space–time evolution of earthquake sequences has been the goal of several investigations, and the increase of seismic activity immediately after large earthquakes, associated with aftershock occurrence, has been long recognized as one of its most prominent properties (e.g., Omori, 1894; Utsu, 1961, 2002). Many efforts have been devoted at understanding the triggering mechanism of the aftershocks in connection with the physical properties of the rocks where mainshocks occur (e.g. Scholz, 1968; Yamashita and Knopoff, 1989; Dieterich, 1994; Correig et al., 1997; Marcellini, 1997; Scholz, 2002; Vidale et al., 2006; Bressan et al., 2012; Velasco et al., 2016). However, one of the basic problems common to the several studies aimed to the characterization and modeling of aftershocks series and, in general, of earthquake sequences (including foreshocks and swarms), is the lack of a unique formal definition. A number of algorithms have been proposed in literature for aftershocks identification (Gardner and Knopoff, 1974; Reasenberg, 1985; Reasenberg and Jones, 1989; Molchan and Dmitrieva, 1992; Zhuang et al., 2002); the most widely used are the window-based methods, which allow for robust declustering, but often require an *ad hoc* adjustment of parameters (Gardner and Knopoff, 1974; Uhrhammer, 1986; Lolli and Gasperini, 2003; Gentili and Bressan, 2008). The absence of a commonly accepted definition of earthquake clusters, clearly affects the possibility of performing their systematic analysis and interpretation. In fact, different methods, relying on different physical/statistical assumptions, may lead to diverse classifications of earthquakes into main events and related events. Thus any consideration based on declustered catalogs, as well as on the extracted clusters, will depend to some extent on the adopted declustering technique. The problem is particularly severe for clusters associated with small and moderate size earthquakes, as in the case of the FVG region. Unlike major quakes, for these events a causative fault can hardly be identified and the low intensity of the aftershocks series makes it difficult to separate them from background activity, except by accurate manual data inspection, which is quite subjective and feasible only for a limited number of clusters.

For these reasons, in this study we decided to apply a formal method that allows for a data-driven identification of earthquake clusters (Zaliapin et al., 2008; Zaliapin and Ben-Zion, 2013a), based on *nearest-neighbor distances* of events in space-time-energy domain (Baiesi and Paczuski, 2004). The intrinsic bimodality of the distribution, which generally characterizes the earthquake nearest-neighbor distances, is used to decompose the seismic catalog into background seismicity and individual sequences of earthquake clusters, including aftershocks and possible foreshocks. The adopted algorithm uses only three parameters (the b-value, the fractal dimension of epicenters, plus a single threshold distance), and can be applied to mainshocks of greatly different magnitude. Moreover, it does not require any underlying assumption about the expected structure of earthquake clusters and permits highlighting and analyzing the hierarchy of links between multiple generations of parent and offspring earthquakes (Zaliapin and Ben-Zion, 2013a). The comprehensive analysis by Zaliapin and Ben-Zion (2013b) in fact, evidenced that the structure of earthquake clusters can be geographically related to the physical characteristics of a region (e.g. heat flow, presence of fluids, etc). Thus we apply this method to systematically identify the aftershock sequences, which occurred in Northeastern Italy during the period 1977–2015, and to differentiate the spatial properties of seismicity, based on the analysis of different topological parameters of the hierarchy.

To characterize the features of seismicity for FVG, we take advantage of updated information from local OGS bulletins, compiled at the National Institute of Oceanography and Experimental Geophysics, Centre of Seismological Research, since 1977. Since a reliable quantification of how seismicity evolves in space and time requires the use of consistent input data, as complete and homogeneous as possible over the analyzed time window, a preliminary reappraisal of the earthquake bulletins is carried out, and the area of sufficient completeness is outlined, as described in Section 3.

In order to estimate the average scaling parameters that characterize the earthquake occurrence in the region, namely the *b*-value and the fractal dimension of epicenters distribution required for the application of the nearest-neighbor technique (Zaliapin et al., 2008), we consider different techniques. Specifically, besides the classical Gutenberg-Richter Law (Gutenberg and Richter, 1954), we apply the Unified Scaling Law for Earthquakes, USLE (e.g. Nekrasova et al., 2011), which permits obtaining both scaling parameters simultaneously, as described in Section 4. The results from clusters identification, obtained by the nearest-neighbor method application in the FVG region for different time intervals and magnitude ranges, are illustrated in Section 5. A detailed comparison of individual earthquake sequences, for the most recent large events reported in the OGS catalog, is carried out to check whether the extracted clusters are consistent with those reported in earlier studies, which were based on event-specific manual aftershocks selection (Gentili and Bressan, 2008). Finally, the characteristic features of seismic clusters are explored, analyzing the relevant space patterns of earthquakes clustering at the Alps-Dinarides transition and its surroundings, in order to identify areas with distinct features of detected cluster types, which can be related to key physical and tectonic properties of the region.

2. Clusters identification by the nearest-neighbor approach

In this study, we identify and analyse the seismic clusters, which occurred in the FVG region during the period from 1977 to 2015, and compare them with manually selected sequences of aftershocks associated with the most significant earthquakes.

To identify earthquake sequences we use a clustering method (Zaliapin and Ben-Zion, 2016 and references therein) based on a generalized definition of distances between pairs of earthquakes in the time–space–magnitude domain, namely the *nearest-neighbor distances* introduced by Baiesi and Paczuski (2004). The method allows for the identification and analysis of seismic clusters; the partition of earthquakes into background seismicity and clusters is facilitated by the bimodal distribution of nearest-neighbor distances (Zaliapin et al., 2008), which is observed in real data, as well as in models of clustered seismicity, including the Epidemic Type Aftershock Sequence, ETAS model (Ogata, 1998).

Given an earthquake catalog, where each record $\{t_i,\phi_i,\lambda_i,d_i,m_i\}$ describes the origin time, location (latitude, longitude and depth), and magnitude of an individual earthquake, for each event *j* it is possible to find its nearest-neighbor *i* and compute the corresponding nearest-neighbor distance ηij. The unique nearest-neighbor of an earthquake is referred to as the *parent*. Each event has a single parent and can be the parent of multiple events, which are called its *offsprings*. The main element used for parent and offspring events identification is the specific distance η_{ij} between any two earthquakes *i* and *j*, as defined by Baiesi and Paczuski (2004):

$$\eta_{ij} = \begin{cases} t_{ij} r_{ij}^{d} 10^{-bm_i}, \ t_{ij} > 0 \\ \infty, \ t_{ij} \leqslant 0 \end{cases} \tag{1}$$

where $t_{ij} = t_j - ti$ is the time elapsed between the two events, $r_{ij} \geq 0$ is the spatial distance between the hypocenters, *b* is the *b-value* from the