Bollettino di Geofisica Teorica ed Applicata Vol. 61, n. 1, pp. 57-80; March 2020
DOI 10.4430/bgta0249

Identification and characterisation of earthquake clusters: a comparative analysis for selected sequences in Italy and adjacent regions

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(Received: 27 June 2018; accepted: 14 September 2018)

ABSTRACT Identification of earthquake clusters has a twofold scope: a) characterisation of clustering features and their possible relation to physical properties of the crust; b) declustering of the earthquake catalogues, to allow for space-time analysis of main-shocks occurrence. Since different methods, relying on different physical/statistical assumptions, may lead to diverse classifications of earthquakes into main events and related events, we investigate the classification differences for three different declustering techniques: the nearest-neighbour approach (NN) and the two widely used windows methods by Gardner-Knopoff and Uhrhammer. A formal selection and comparative analysis of earthquake clusters is carried out for selected earthquakes in north-eastern Italy and adjacent regions, as reported in the OGS catalogue since 1977. The comparison is, then, extended to earthquake sequences associated with strong earthquakes in central Italy, occurring in a different seismotectonic setting, by making use of INGV data over the period 1981-2017. The NN data-driven approach turns out well consistent with classical window approach for large events, while improving clusters identification in areas characterised by low to moderate seismic activity, where windowing methods necessitate adequate optimisation. Moreover, the declustering performed by NN method preserves the features of inhomogeneous and possibly non-stationary background seismicity, relevant for several studies.

Key words: earthquake clusters, aftershocks, declustering, nearest-neighbours, window methods.

1. Introduction

A number of studies aimed at seismic hazard assessment, as well as at the space-time analysis of earthquakes occurrence, require preliminary declustering of the earthquake catalogues. Moreover, the identification and statistical characterisation of seismic clusters may provide useful insights about the features of seismic energy release and their relation to physical properties of the crust within a given region (e.g. Peresan and Gentili, 2018). Earthquake clustering, in fact, is a fundamental aspect of seismicity, with typical features in space, time, and energy domains that provide key information about earthquake dynamics. Nevertheless, in spite of the overall agreement about the existence of different types of clusters (aftershocks, swarms, etc.), there is no agreed formal definition, nor a unique method to identify them.

Several methods have been proposed so far for clusters identification and catalogues declustering (e.g. Gardner and Knopoff, 1974; Reasenberg, 1985; Reasenberg and Jones, 1989; Molchan and Dmitrieva, 1992; Zhuang *et al*., 2002). Most of the declustering algorithms available in literature are based on a deterministic space-time-window scheme or on a stochastic branching model [e.g. ETAS model by Ogata (1998)], which are generally suitable for large earthquakes, characterised by evident aftershock series clearly emerging from the background seismicity. The window-based methods, in particular, are the most widely used, since they allow for a robust declustering, although often require an *ad hoc* adjustment of parameters (Gardner and Knopoff, 1974; Uhrhammer, 1986; Lolli and Gasperini, 2003; Gentili and Bressan, 2008; Gentili, 2010). 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 catalogues, as well as on the extracted clusters, will depend to some extent on the adopted declustering technique. The problem is particularly difficult for clusters associated with small and moderate size earthquakes, as in the case of the recent seismicity in north-eastern Italy and western Slovenia since 1977. Unlike major quakes, for these events a causative fault can hardly be identified and the low level of aftershocks activity makes it difficult to separate them from the background activity, except by accurate manual data inspection, which remains quite subjective and feasible only for a limited number of clusters (e.g. Gentili and Bressan, 2008).

Since various methods, relying on different physical/statistical assumptions, may lead to diverse classifications of earthquakes into main events and related events, we investigate the classification differences among different declustering techniques. Three different techniques, including two classical space-time windows methods (Gardner and Knopoff, 1974; Uhrhammer, 1986), are considered for this purpose. The third one is a statistical method for detection of earthquake clusters, based on “nearest-neighbour distances” of events in the space-time-energy domain (Baiesi and Paczuski 2004; Zaliapin *et al*., 2008). This method allows for a robust data-driven identification of seismic clusters, and permits to disclose possible complex features in the internal structure of the identified clusters (e.g. Zaliapin and Ben-Zion, 2013a; Daskalaki *et al*., 2014, 2016). Accordingly, a formal selection and comparative analysis of earthquake clusters is carried out for the most relevant earthquakes in north-eastern Italy and western Slovenia. The comparison is then extended to selected earthquake sequences associated with a different seismotectonic setting, namely to events that occurred in the region struck by the 2016 central Italy destructive earthquakes sequence and its surroundings, including the Colfiorito (1997) and L'Aquila (2009) sequences.

The similarities and basic differences between the clusters, identified by the nearest-neighbour (NN) method and using other approaches, are investigated for the selected sequences. A detailed comparison of individual earthquake clusters, for the most recent large events reported in the OGS catalogue, is carried out to check whether the extracted clusters are consistent with those reported in earlier studies, which were based on event-specific manual aftershock selection (Gentili and Bressan, 2008). The study shows that the data-driven approach, based on the NN distances, can be satisfactorily applied to decompose the seismic catalogue into background seismicity and individual sequences of earthquake clusters, also in areas characterised by moderate seismic activity, where the standard declustering techniques may turn out rather gross approximations. With these results acquired, the main features of the identified clusters are explored, with the aim to analyse earthquake sequences in north-eastern Italy and western Slovenia, an area characterised by both compressional and shear deformation mode, and capture their basic differences with central Italy sequences, where the deformation mode is prevalently extensional.

2. Clusters identification methods

2.1. The nearest-neighbour approach

In this study, earthquake clusters are identified applying a novel statistical approach, which is based on the NN distances η between pairs of earthquakes in the space-time-energy domain (Baiesi and Paczuski, 2004). The distance η_{ij} between any earthquake j to an earlier earthquake i is defined as:

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

where $t_{ij} = t_j - t_i$ is the inter-occurrence time; r_{ij} is the epicentral distance between the two earthquakes; d corresponds to the fractal dimension of epicentres and b is the slope parameter of the Gutenberg-Richter law in the study area. The NN distance can be equivalently decomposed into the corresponding rescaled space (R_{ij}) and rescaled time (T_{ij}) distances from the parent to its offspring event (Zaliapin *et al.*, 2008), namely $\eta_{ij} = T_{ij} R_{ij}$, where space and time distances are rescaled depending on the magnitude of the parent event:

$$T_{ij} = t_{ij} 10^{-bm_i/2}, \quad R_{ij} = {r_{ij}}^{d} 10^{-bm_i/2} \tag{2}$$

It has been demonstrated by Zaliapin *et al*. (2008) that the 1D empirical distribution of the NN distances η and the 2D density map of its components (R, T), which are obtained from models of Poissonian seismicity and individual clusters, are both unimodal, although the cluster distribution is centred around much shorter space-time distances. On the other side, the distributions that are obtained from real seismicity and from models of clustered seismicity [including Epidemic Type Aftershock System, ETAS model: Ogata (1998)], are prominently bimodal because of the different location of the distributions of distances η, R and T associated with background and clustered activity. This bimodality can be used to separate earthquakes into background seismicity and cluster populations (Zaliapin and Ben-Zion, 2013a). Specifically, clusters are formed by earthquakes that are sufficiently close in the space-time-energy domain, namely by events with NN distances not exceeding a specified threshold, that is $\eta_{ij} < \eta_0$. The threshold η_0 can be selected following a criterion based on a 1D Gaussian mixture model with two modes, where η_0 is the maximum likelihood boundary between the two modes.

By connecting each event with its nearest neighbour, identified according to the distance η_{ij}, one obtains a time-oriented tree, whose root is the first event in the catalogue (Baiesi and Paczuski, 2004). Removing all connections associated with large parent-offspring distances (i.e. $\eta_{ij} > \eta_0$) it is possible to separate individual earthquake clusters. Clusters composed by a single event are referred as “singles”, those composed by several events are referred as “families”. The largest earthquake within a family is the “main shock”; all events in the family following the main shock are called “aftershocks”, those preceding it are called “foreshocks”. All singles are considered as main shocks. If the largest magnitude event occurs in the middle of a cluster and the family includes other events of comparable magnitude, then the cluster is referred as "swarm". Essentially, earthquake swarms correspond to clusters that exhibit a gradual rise and fall in seismic moment release, lacking a clear mainshock-aftershocks pattern (Mogi, 1963; Yamashita, 1998). Each family has a tree structure and the links from the main shock to related events can be analysed, so as to identify typical features that characterise the topological structure of the earthquake cluster.

The NN technique provides a robust, data-driven tool to uniformly identify clusters associated with main shocks from a wide magnitude range. The method requires only three input parameters: the *b*-value, *b*, the fractal dimension of epicentres, *d*, and a single threshold distance, η_0. The absence of underlying assumptions about the expected earthquake cluster structure makes it especially suitable to identify new robust features of observed seismicity and to explore possible spatial patterns of earthquakes clustering. As shown by Zaliapin and Ben-Zion (2013a), in fact, the removal of clusters identified by this procedure does not alter the features of inhomogeneous and possibly non-stationary background seismicity, which are relevant for many studies (e.g. Gentili *et al*., 2017). We refer to Zaliapin and Ben-Zion (2016) for further details on the NN approach.

2.2. Window methods

We also consider standard windowing methods for earthquake declustering. Window-based methods define a time interval τ and a circular area of radius ρ, where τ and ρ are functions of the mainshock magnitude M_m. Among all the earthquakes, only the ones within the time-space distance τ and ρ from the mainshock are considered as belonging to the cluster. Several different functions of M_m have been proposed for τ and ρ in the literature (Gardner and Knopoff, 1974; Uhrhammer, 1986; Molchan and Dmitrieva, 1992; Knopoff, 2000; Lolli and Gasperini, 2003; Gentili and Bressan, 2008). We applied and compared the performances of two different algorithms with NN approach: that by Gardner and Knopoff (1974) (GK) and that by Uhrhammer (1986) (U).

The U equations for ρ and τ are given by:

$$\rho = e^{-1.024+0.804*M_m} \tag{3}$$

and

$$\tau = e^{-2.87+1.235*M_m} \tag{4}$$

GK supplied a table with the values of ρ and τ for different magnitude M_m of the mainshock.

For $M_m < 6.5$ the table is commonly substituted by the following approximation (see e.g. van Stiphout *et al*., 2012).

$$\rho = 10^{0.1238*M_m+0.983} \tag{5}$$

and

$$\tau = 10^{0.5409*M_m-0.547} \tag{6}$$

In both cases, ρ is expressed in km and τ in days after the mainshock.

Fig. 1 shows the comparison between the two methods. For magnitudes smaller than 6.5 GK method supplies longer τ and ρ compared with U ones.

The window methods are straightforward. However, the length and duration of space-time windows are not unique and usually do not result from an optimisation procedure, accounting for region specific properties of seismicity and data.

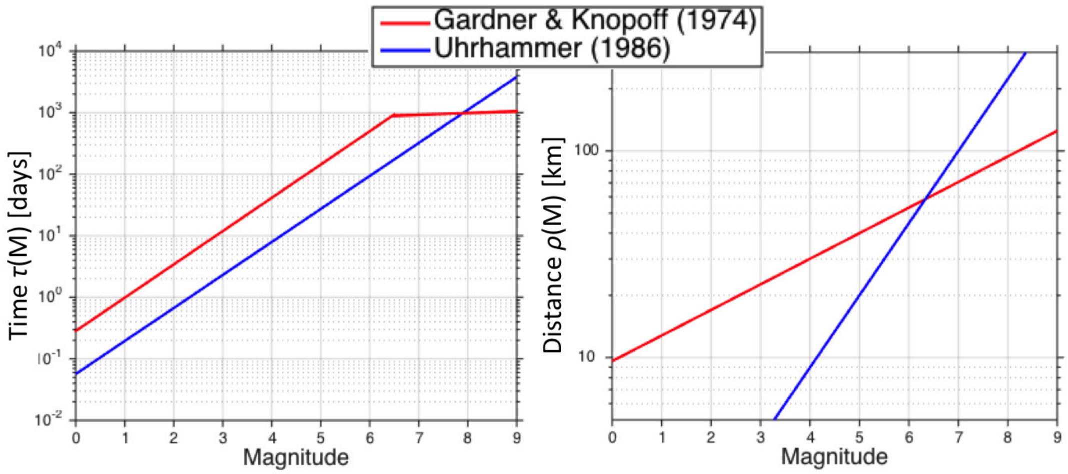

Fig. 1 - Size of the space and time windows used by the windows methods GK and U [see van Stiphout *et al.* (2012) for further details].

3. The earthquake data

A formal selection and comparative analysis of earthquake clusters is carried out for the most relevant earthquakes in north-eastern Italy and western Slovenia (hereinafter referred as North-eastern Region), close to the Italian border, as reported in the bulletins compiled at the Istituto Nazionale di Oceanografia e di Geofisica Sperimentale - OGS (Gentili *et al*., 2011; Peresan and Gentili, 2018). The analysis is, then, extended to consider earthquake clusters occurred in an area characterised by a different seismotectonic setting, namely the area struck by the central Italy earthquake sequence in 2016-2017. For this purpose we consider the instrumental database of Italian seismicity, which is composed by the catalogue of Lolli and Gasperini (2006) and is updated since 2005 using the data from the Italian Seismological Instrumental and parametric Data-basE, ISIDE (iside.rm.ingv.it/iside).

3.1. North-eastern Region

The North-eastern Region is located at the Alps-Dinarides transition, with a dominant mode of deformation changing from compressional to shear (with dextral strike-slip motion), when moving from west to east. Seismicity concentrates along the almost E-W trending Alpine fault system and along the NW-SE trending Dinaric fault system. Earthquakes are shallow (mostly in the depth range 6-12 km and even shallower) and have fault plane solutions prevalently of thrust type in the western part and strike-slip in the eastern one, with minor normal faulting events (Bressan *et al*., 2016 and references therein).

The study region experienced several destructive earthquakes in the past, the most recent one being the *M* 6.4 1976 Friuli earthquake (Slejko *et al*., 1999; Slejko, 2018). The main events occurred during the last two decades are the 12 April 1998 (*M* 5.6) and the 12 July 2004 (*M* 5.1) earthquakes, both located nearby the border between Italy and Slovenia. The instrumental seismic activity recorded so far, however, is prevalently characterised by the occurrence of low to moderate earthquakes, only sporadically exceeding magnitude 4.0.

In order to analyse the seismicity of North-eastern Region, we, therefore, resort to the local bulletins compiled at the Seismological Research Centre (CRS) of OGS since 1977 (hereinafter referred as OGS catalogue), which are routinely updated and made available via the following web site: www.crs.ogs.trieste.it/bollettino/RSFVG/RSFVG.en.html. The considered catalogue includes 24,279 events, which occurred in the period 6 May 1977 - 31 December 2015, with coda-duration magnitude (Rebez and Renner, 1991) in the range $0<M_d\leq5.6$. A preliminary data reappraisal was carried out by Peresan and Gentili (2018) to allow for the identification of missing events, removal of spurious records, duplicates and explosions (Peruzza *et al*., 2015), as well as to assess homogeneity and completeness of data in space and time [see Gentili *et al*. (2011) for a review]. Accordingly, a region has been outlined by Peresan and Gentili (2018), which encompasses the most active areas in north-eastern Italy, and where the data are robustly and homogeneously complete in space and time. The frequency-magnitude distributions of earthquakes obtained from the OGS catalogue indicate that, within the identified area, it can be considered confidently complete for magnitudes $M\geq M_c=2.0$ for the whole time span 1977-2015, and at least for $M\geq M_c=1.5$ since 1994.

3.2. Central Region

In central Italy, crustal seismicity concentrates along a narrow belt beneath the Apennines. The Apennines resulted from the contemporaneous opening of the Tyrrhenian Sea, the eastward migration of a compressive front, and the retreat of the lithospheric plate dipping below the Italian peninsula (Malinverno and Ryan, 1986; Doglioni, 1991, 1995). Seismological data and recent geodetic studies revealed that the central Apennines are undergoing a NE-trending extension, and that seismic deformation rates are higher in the southern Apennines (Anderson and Jackson, 1987; Westaway, 1992; Pondrelli *et al*., 2002; Hunstad *et al*., 2003). The NW-SE striking normal faults that affect the Apennines are prone to medium-large earthquakes and they are considered responsible for the largest historical earthquakes (e.g. in 1688 and 1805, $I_o\geq10$ MCS), early instrumental earthquakes (1962, M_s = 6.1; 1980, M_s = 6.9, Valensise and Pantosti, 2001) and recent normal faulting earthquakes. NE-SW striking faults dissect the Apennines (Oldow *et al*., 1993; Sorgi *et al*., 1998), and low-magnitude earthquake swarms are located along these faults at the tips of the main NW-SE striking faults (Valensise and Pantosti, 2001; Milano *et al*., 2002, 2008).

The catalogue used in this work covers a quite large area (latitude = 40-46° N and longitude = 10-15° E), and a time span of over 35 years, from 1981 to March 2017. Specifically, we use the catalogue of Lolli and Gasperini (2006), which has been obtained by merging different complementary catalogues: the CSTI (Gruppo di lavoro CSTI, 2001) that covers the 1981-1996 period, the CSI for the period 1997-2002 (Castello *et al*., 2006), and the Italian Seismic Bulletin (http://bollettinosismico.rm.ingv.it/) for the period January 2003 - December 2004. From 2005 we use data from ISIDE (2017) compiled at the Istituto Nazionale di Geofisica e Vulcanologia

(INGV), and from ISIDE web-site (http://iside.rm.ingv.it/iside/; last accessed on 5 March 2017).

In order to reduce magnitudes heterogeneity (Peresan *et al*., 2000), in the catalogue by Lolli and Gasperini (2006) all magnitude estimates were homogenised to local magnitude M_L. The resulting catalogue reports 38,900 events with M_L>2.0. The completeness level of the ISIDE catalogue in central Italy has been assessed as M_c=2.2 (Romashkova and Peresan, 2013; Gentili *et al*., 2017). For the first part of the catalogue, that is before 2005, the completeness magnitude is higher and depends on the specific area and time interval: specifically, till 1985 M_c can be estimated in the range 2.7-3.0, while it decreases to 2.2-2.4 after 1990. Thus, a conservative completeness magnitude threshold for the overall time span 1981-2017 can be fixed at M_c= 3.0.

3.3. Scaling parameters

The application of the NN technique requires preliminary estimation of the scaling parameters *b* and *d*, namely the *b*-value of the Gutenberg-Richter law (Gutenberg and Richter, 1954) and the fractal dimension of epicentres distribution (e.g. Grassberger, 1983), within the study region. For this purpose, we resort to the Unified Scaling Law for Earthquakes (USLE) (Kossobokov and Mazhkenov, 1988; Nekrasova *et al*., 2011), which permits dealing with both parameters simultaneously.

To quantify the scaling parameters of earthquake occurrence in North-eastern Region, the USLE has been applied to the revised OGS catalogue, limited to the period of improved seismic acquisition and data completeness, from 1 July 1994 to 31 December 2015. The parameters of the USLE have been computed at different spatial resolution, considering earthquakes down to magnitude 1.5 [see Peresan and Gentili (2018) for further details]. The consistency of the USLE coefficients with classical estimates of *b*-value from the Gutenberg and Richter (1954 : GR) law, and fractal dimension (Grassberger, 1983; Rossi, 1990), has been assessed as well. Accordingly, the following robust estimates are used hereinafter b = 0.9-1.0 and d = 1.0-1.1 as standard coefficients for the identification of earthquakes clusters in North-eastern Region, based on NN distances from Eq. 1.

For the Central Region, the scaling parameters of seismicity have been defined according to the USLE coefficients estimated by Nekrasova *et al*. (2011), namely: b = 0.8-1.0 and d = 1.3-1.4. In fact Nekrasova *et al*. (2011) showed that also in the central part of Italy the *b*-value estimated on the base of USLE provides consistent estimates of the average balance of magnitude over large regions, compared to other classical estimates (e.g. Kronrod and Molchan, 2004).

Given the completeness threshold M_c, and the scaling parameters *b* and *d,* thus defined for the two regions, the NN distances η_{ij} (as well as the corresponding rescaled space and time distances R_{ij} and T_{ij}) could be computed and analysed. The parameters *q* and *p* are set to $q = p = 0.5$, the latter implying that equal weight is assigned to space and time components; this choice, however, does not affect the NN distances η_{ij} nor the related 1D distribution, thus it has no influence on clusters identification.

Within the Central Region both the 1D distribution of η_{ij} and the 2D density map of *(R, T)* for the analysed area turn out bimodal, with a well-defined separation between the two peaks (see Fig. 2b). Accordingly, the threshold is automatically set on a value of $\log_{10}\eta_0$ = -4.3. On the other side, within the North-eastern Region the 1D distribution of η_{ij} is characterised by a dominant background component (right peak) and by a much less pronounced clustered component (left peak), which eventually complicates the identification of the appropriate threshold η_0 for the separation of the two components (Fig. 2a). Therefore, for this region the threshold distance is manually set on a value of $\log_{10}\eta_0$ = -5.0, so that a more conservative declustering of the catalogue is performed (i.e. less events are identified as aftershocks). By selecting the threshold distance smaller than the automatic threshold, which is about $\log_{10}\eta_0$ = -4.1, we exclude almost completely background seismicity from clusters (i.e. red curve in Fig. 2a).

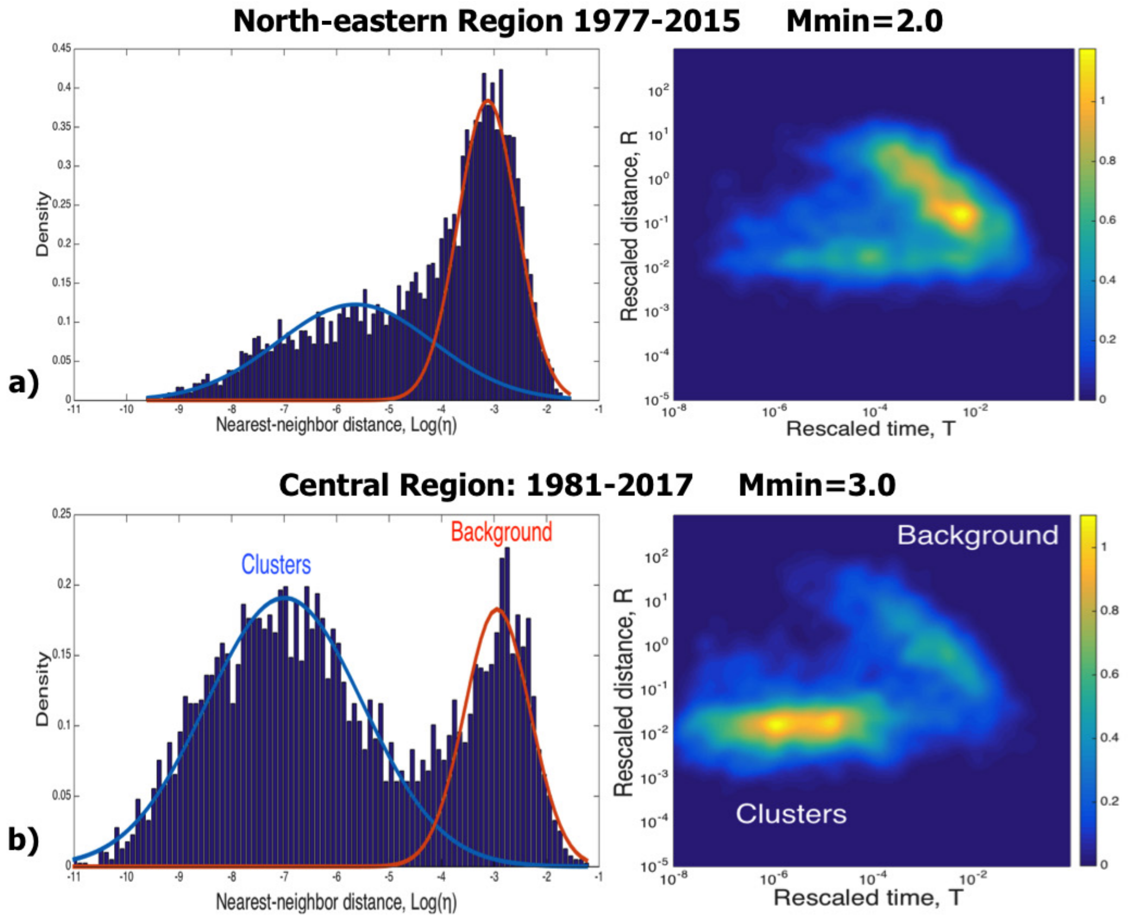

Fig. 2 - NN method applied to seismicity of: a) North-eastern Region (1977-2015) and b) Central Region (1981-2017). Left column: 1D density distribution of η, with estimated Gaussian densities for clustered (blue) and background (red) components. Right column: 2D joint distribution of rescaled space and time distances *(R, T),* with $p = q = 0.5$. Distributions are obtained considering the following scaling parameters: $b = 0.9$ and $d = 1.1$ in the North-eastern Region; $b = 1.0$ and $d = 1.4$ in the Central Region. The minimum magnitude (M_{min}) considered in the analysis corresponds is specified on the top of the plots.

4. Comparative analysis of aftershocks sequences

Zaliapin and Ben-Zion (2013a) already demonstrated, based on California seismicity, that the earthquake clusters detected by NN method reproduce the main statistical features of aftershocks series reported in literature, including the Omori Law and Båth Law (e.g. Utsu *et al.*, 1995). In order to verify whether this statistical approach allows for a realistic identification of seismic sequences, possibly improving catalogues declustering, the aftershocks formally identified by the NN method are compared with those selected by different methods for the most significant recent earthquakes, which occurred within the study regions.

The overall features of declustered catalogues are examined for both the analysed regions. A summary statistic of earthquake data, focused on restrained well monitored areas including the relevant sequences, is provided in Table 1 for two different time-magnitude ranges. We observe that within the selected areas the percentage of events included in clusters is grossly around 30% in the North-eastern Region and around 80% in Central Region, independently from the declustering approach. Accordingly, the clustered component of seismicity turns out to be prevalent in central Italy, while it is quite limited in North-eastern Region, thus confirming observations from Fig. 2 and supporting the essential difference in seismic energy release in the two areas. This is particularly evident for the most recent time interval 2005-2017, when seismicity of Central Region is dominated by the two prominent sequences, associated with the L'Aquila (2009) and Norcia (2016) earthquakes. Moreover, it can be observed that the number of clustered events selected by the NN method is lower than that from the GK method within the North-eastern Region, while in the Central Region it is the opposite, namely the number of events in clusters is larger for NN than for GK. This is possibly due to the conservative manual selection of the threshold log η_0 = -5.0 in North-eastern Region; here, in fact, using the automatic threshold (i.e. log η_0 = -4.1) the number of events included in clusters increases significantly (Nclust = 2072 in the time span 1994-2015, that is about 43% of events with $M \geq 1.5$) and becomes larger than that from GK. At the same time, the U method provides a systematically lower rate of clustered events, compared to the NN and GK methods, in both regions.

To further explore the differences between the considered declustering methods, the space-time pattern of earthquakes occurrence is examined, comparing the full and the declustered catalogues. The seismicity and mainshock sequences identified within the Central Region since 2005 (Fig. 3) well exemplify the situation: in the full catalogue (Fig. 3a) the clusters are clearly visible, while they almost completely disappear after NN declustering (Fig. 3b), yet preserving certain patterns of background seismicity. Remarkably, the GK declustering creates an evident

Table 1 - Number of earthquakes in clusters (Nclust) vs. the number of all events (N), within the specified space-time-magnitude volumes. M_c is the magnitude completeness threshold estimated for the corresponding time window. Earthquake clusters have been identified by the NN method, considering: a) the fixed threshold distance log η_0 = -5.0, and scaling parameters b = 0.9 and d = 1.1 in the North-eastern Region; b) the threshold distance log η_0 = -4.33, and scaling parameters b = 1.0 and d = 1.4 in the Central Region.

	Area	**Time interval**	M_c	**N All events**	**Nclust NN (%)**	**Nclust GK (%)**	**Nclust U (%)**
North	Lat.: 45.5-46.5° N Lon.: 12.0-14.0° E	1977-2015	2.0	3939	1145 (29.1%)	1397 (35.5%)	999 (25.4%)
		1994-2015	1.5	4798	1426 (29.7%)	1726 (34.0%)	1279 (25.2%)
Centre	Lat.: 41.0-45.0° N Lon.: 12.5-14.0° E	2005-2017	2.2	11340	9902 (87.3%)	9384 (82.8%)	8956 (79.0%)
		1981-2017	3.0	2465	1967 (79.8%)	19176 (77.7%)	1780 (72.2%)

seismicity gap (Fig. 3c) immediately following the main L'Aquila earthquake in 2009. On the other side, clusters are still visible in the catalogue of mainshocks obtained by U method (Fig. 3d), thus suggesting that this method does not allow for an efficient declustering.

The situation is very similar in North-eastern Region (Fig. 4), where the GK declustering determines sharp seismicity gaps (Fig. 4c) in the space-time vicinity of major earthquakes (e.g. the 1998 and 2004 Kobarid events), while the U method provides a very limited declustering (Fig. 4d). Compared to Central Region, here the NN method turns out less effective in catalogues declustering (i.e. some aftershocks might still be included in the catalogue, as it appears from Fig. 4b), because of the conservative choice of threshold log η_0 for clusters identification made in this region. Still, the use of the fixed threshold allows for a more reliable identification of clustered events, and hence it seems preferable, as discussed in some detail in the following.

The overall features of the declustering methods mentioned so far are stable and robust. For the NN method, in particular, it is found that a different choice of the time span, and the related minimum magnitude M_c, does not alter substantially the overall partition of seismicity into background and clustered components (Table 1). With these results acquired about the general performances of the considered methods, in the following we investigate in some detail the differences in the identification of individual seismic clusters. Specifically, the aftershocks sequences selected by the different methods are compared for the most significant recent earthquakes, which occurred within the study regions.

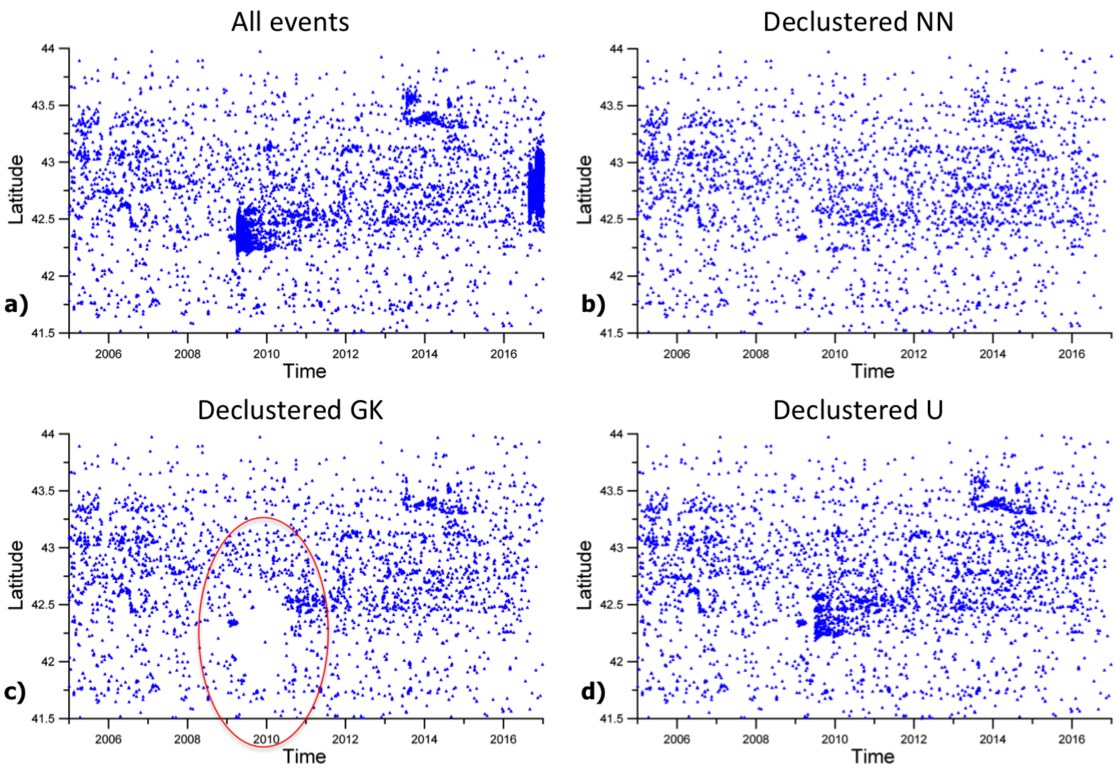

Fig. 3 - Space-time pattern of earthquakes occurrence in the Central Region, for: a) all events and mainshocks identified by b) NN method; c) GK method and d) U method. Only earthquakes with $M \geq 2.2$ in the range: latitude = 41.0-45.0°, longitude = 12.5-14.0° are included in the analysis. The red circle highlights the gap determined by GK declustering after the 2009 (M 6.3) L'Aquila earthquake.

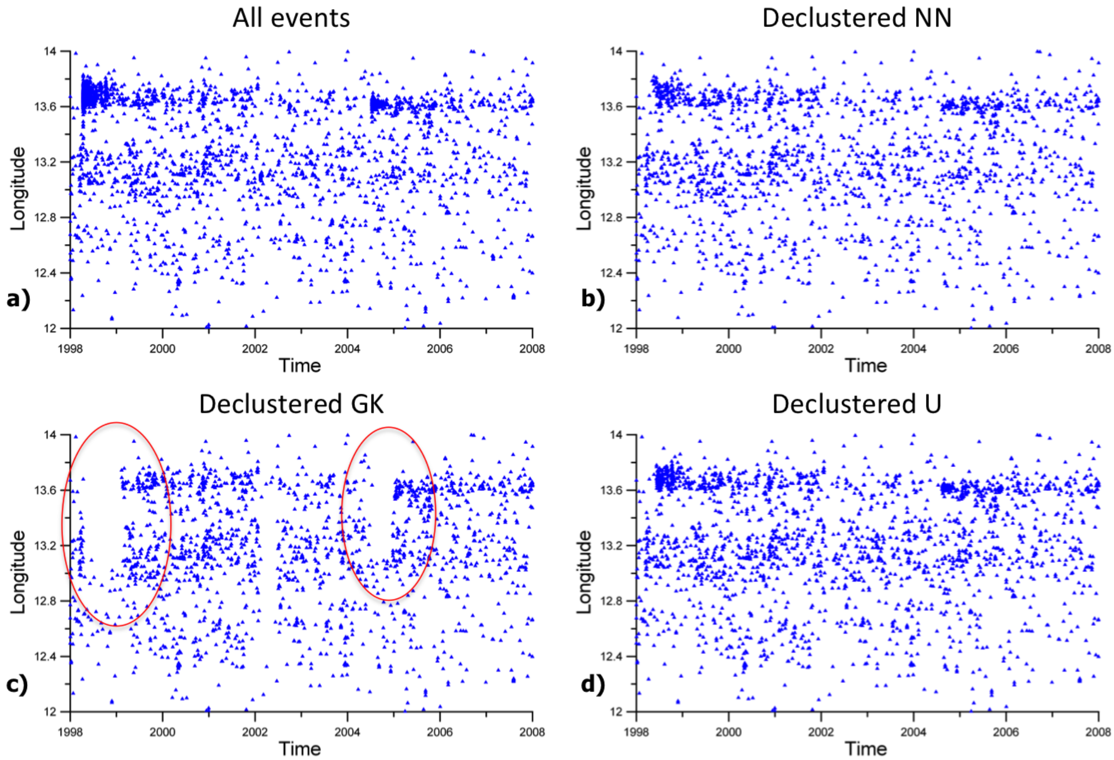

Fig. 4 - Space-time pattern of earthquakes occurrence in the North-eastern Region, for: a) all events and mainshocks identified by b) NN method; c) GK method and d) U method. Only earthquakes with $M \geq 1.5$ in the range: latitude = 45.5-46.5°, longitude = 12.0-14.0° are included in the analysis. The red circles highlights the gaps determined by GK declustering after the two main 1998 (M 5.6) and 2004 (M 5.1) Kobarid earthquakes.

4.1. North-eastern Region

The analysis performed so far evidenced that recent seismicity within the North-eastern Region has a prevalent background component, while the clusters component is very limited (Fig. 2a). This feature can be basically explained by the fact that during the operation time of the OGS network, which was operated one year after the 1976 Friuli earthquake [M_L 6.4, see Slejko (2018)]), only a limited number of moderate size events and related clusters occurred in the region, with magnitudes not exceeding 5.6. Thus, earthquake sequences correspond to a rather small portion of recorded events (Table 1), which ultimately complicates their formal identification and statistical characterisation. In fact, as already pointed out by Peresan and Gentili (2018), the use of the automatic threshold would lead to include in clusters a number of earthquakes that can be very distant in space and time, mostly belonging to background activity (Fig. 5). This effect is particularly relevant in North-eastern Region, because of the significant overlapping and unclear separation between the two Gaussian distributions associated with background and clustered components (Fig. 2a, left panel). Therefore, in the following comparative analysis we refer to the manually defined threshold, which provides a possibly less complete, but more reliable declustering (i.e. some aftershocks might not be removed, but at the same time the number of events improperly included in clusters is almost negligible).

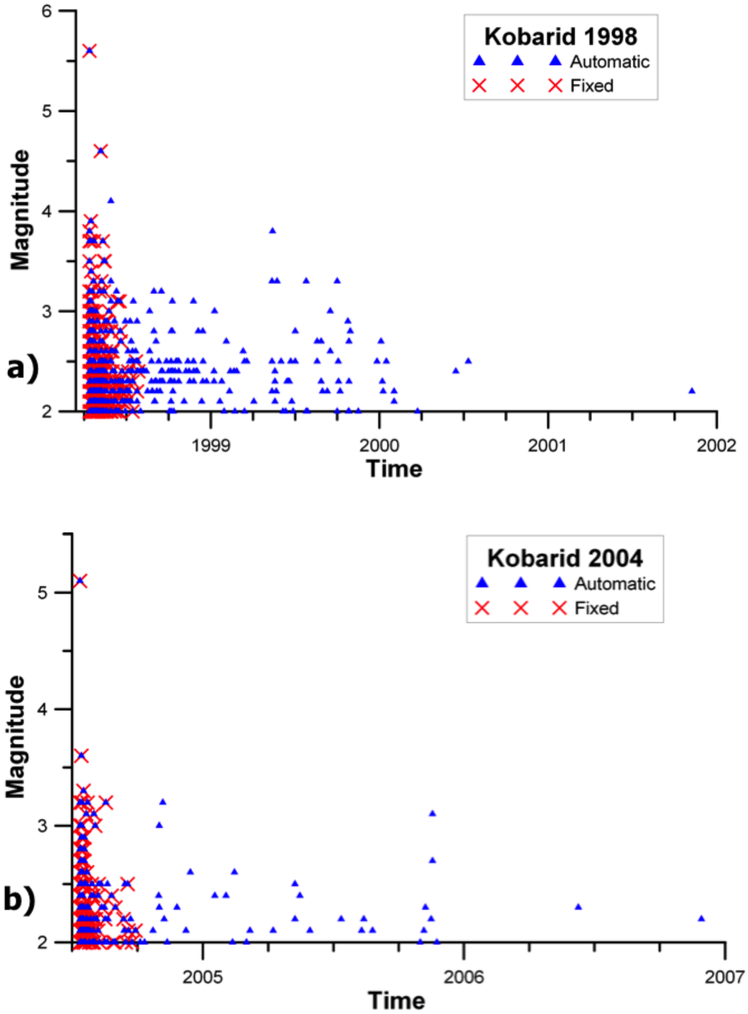

Fig. 5 - Comparison of sequences associated with the 1998 and 2004 Kobarid earthquakes, as identified by the NN method for two different threshold distances: automatically defined threshold log η_0=-4.1 (blue) and fixed threshold log η_0=-5.0 (red). Sequences were extracted considering the OGS catalogue for the time interval 1977-2015, M_c=2.0 and scaling parameters b=0.9 and d=1.1.

The comparison between sequences extracted by the NN statistical approach and by the GK and U window methods is carried out for the two most large earthquakes reported in OGS catalogue, namely the Kobarid 12 April 1998 (M 5.6) and Kobarid 12 July 2004 (M 5.1) earthquakes, considering aftershocks with $M \geq 2.0$. The comparison is then extended to smaller magnitude events, considering the two additional Sernio, 14 February 2002 (M 4.9) and Valdobbiadene, 12 May 2015 (M 3.7) earthquakes. Given their location and occurrence time, which guarantees sufficient completeness of data, for the last two events the analysis is extended down to magnitude M=1.0 (Peresan and Gentili, 2018). The location of the four selected clusters, as identified by the NN method, is shown in Fig. 6.

The comparative analysis of individual earthquake clusters shows that the GK window method overestimates the spatial and temporal extent of the sequences for both the moderate size and the small quakes, compared to NN and U method (Figs. 7 and 8). On the other side, the U window method tends to cut the sequences very short in time, even shorter than the NN method with the conservative fixed threshold. Still the clusters identified by the U and NN methods display a very consistent spatial extent (Fig. 8), with an almost identical maximum distance of events from the mainshock (Dist_max in Table 2). The number of events in the sequence is very similar for U and NN methods (see Table 2) while GK method tends to overestimate it.

Table 2 - Number of aftershocks included in each cluster (Num), maximum distance from the mainshock (Dist_max, in km) and duration (Time, in days) for each of the four selected sequences. Earthquake clusters have been identified by the NN method, considering: a) the fixed threshold distance log η_0=-5.0, and scaling parameters b=0.9 and d=1.1.

		Earthquake sequence			
		KOB-1998	**KOB-2004**	**SER-2002**	**VAL-2015**
	M_{main}	5.9	5.1	4.9	3.7
	M_{min}	2.0	2.0	1.0	1.0
NN	**Num**	479	146	32	28
	Dist_max	31	9	16	4
	Time	106	78	55	15
GK	**Num**	690	181	61	34
	Dist_max	50	42	41	29
	Time	299	162	125	20
U	**Num**	471	135	37	26
	Dist_max	32	9	17	5
	Time	57	30	22	6

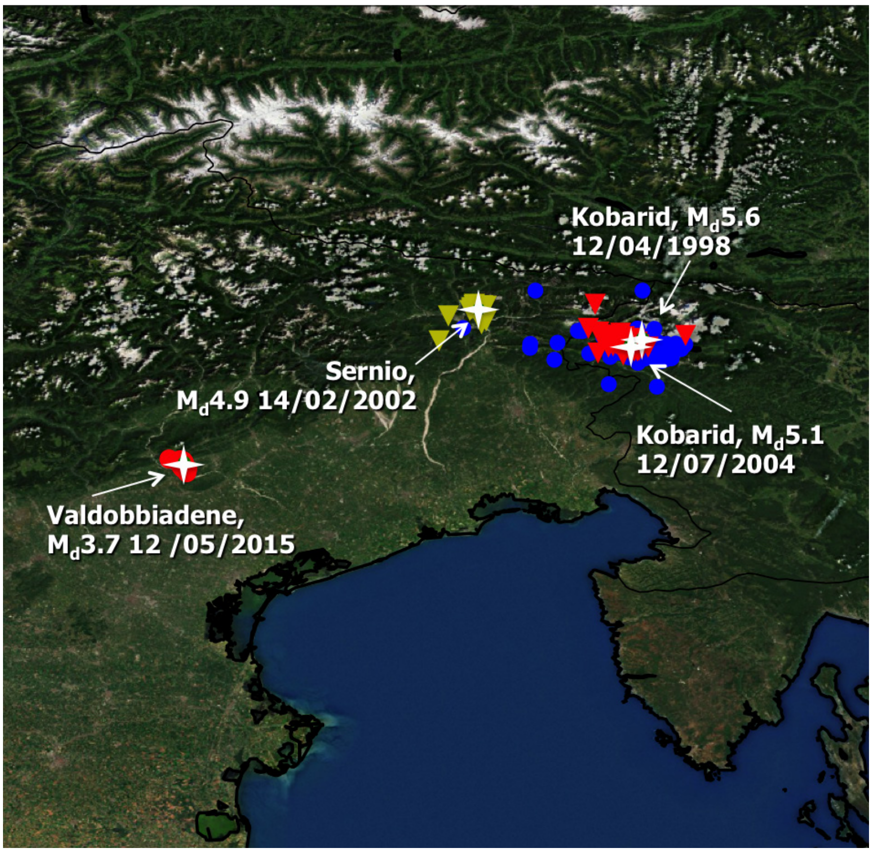

Fig. 6 - Location of clusters, as identified by the NN method, for the four selected sequences in the North-eastern Region: Kobarid 1998 (blue dots) and 2004 (red triangles), Sernio 2002 (yellow triangles) and Valdobbiadene 2015 (red dots). White stars mark the epicentres of the mainshocks from each cluster.

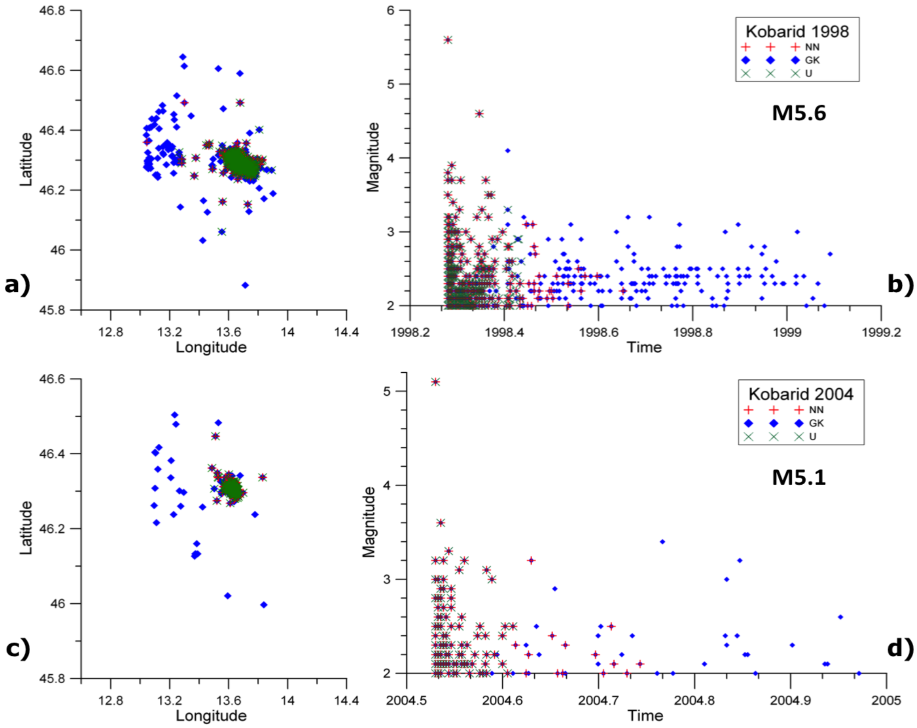

Fig. 7 - Comparison of the clusters associated with the 1998 and 2004 Kobarid earthquakes, as identified by the NN, GK and U methods: coordinates (left) and magnitude vs. time (right) plots of the events composing the clusters.

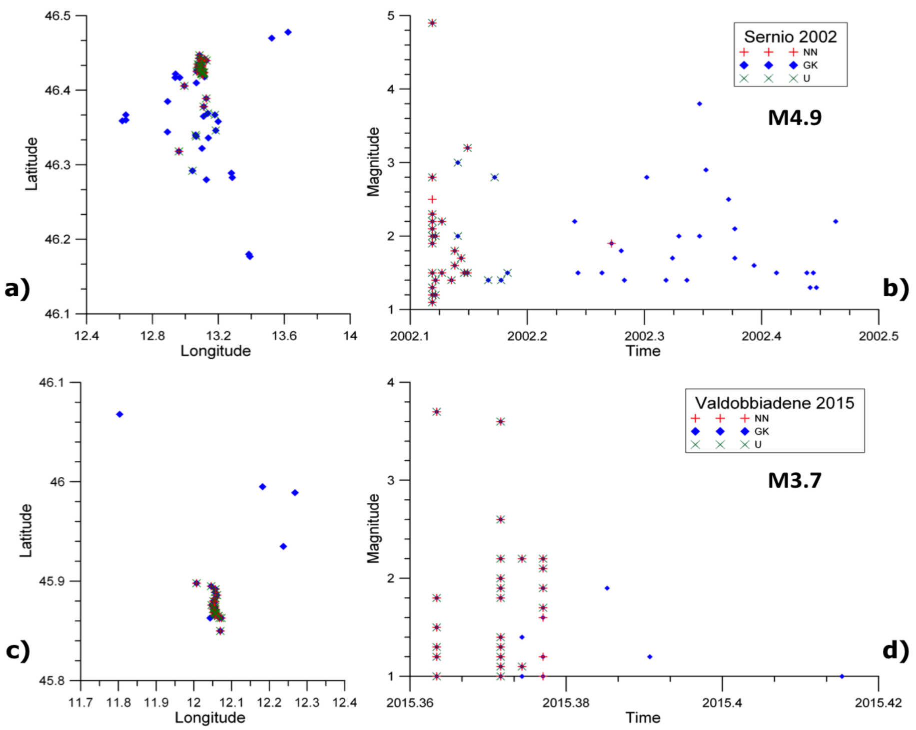

Fig. 8 - Comparison of the clusters associated with the Sernio 2002 and Valdobbiadene 2015 earthquakes, as identified by the NN, GK and U methods: coordinates (left) and magnitude vs. time (right) plots of the events composing the clusters.

4.1.1. Comparison with manually identified sequences

In this section, we compare the seismic clusters identified by NN statistical approach, with the manually identified sequences of aftershocks, associated with the following three earthquakes: Kobarid 1998 and 2004, and Sernio 2002. The main clusters of seismicity from 1997 to 2007, in fact, were studied by Gentili and Bressan (2008), by manually selecting the clusters in order to calibrate a time and space window method, with size optimised to earthquake sequences recorded in the study area. Specifically, the sequence duration t was obtained assuming that the analysed sequence ended when the rate became constant for at least 6 months time, the radius ρ of the circular area including the whole sequence was selected as the one for which the rate of seismicity did not vary with increasing radius. The joint analysis of the relation between the mainshock magnitude (in M_d units) and the ρ (in km) and τ (in days) values for the sequences allowed Gentili and Bressan (2008) to define the following equations for the aftershocks space-time windows, which apply to seismicity of north-eastern Italy and western Slovenia:

$$\rho = 10^{0.41M-1} \qquad (7)$$

$$\tau = 10^{0.33M+0.42} \qquad (8)$$

Accordingly, for the M 5.6 1998 earthquake the considered space-time window could be defined as ρ = 20 km radius and τ = 185 days (about six months), for the M 5.1 2004 earthquake it results ρ = 12 km and τ = 127 days (about four months) and for the M 4.9 2002 earthquake, ρ = 10 km and τ = 109 days (about three months). Finally, for the M 3.7 2015 earthquake, we get ρ = 3 km and τ = 44 days (about one and a half months). These values can be compared with those reported in Table 2. The spatial distance ρ optimised to the manually selected sequences, turns out comparable or even smaller than the maximum distance from NN and U methods (which are almost identical), while it is much smaller (less than half) than GK windows. On the other side, the temporal duration of manual sequences is longer than NN, but still lower than GK. Compared to all the other methods, U cuts the sequences much shorter in time. A peculiar behaviour is observed for the Sernio 2002 sequence, for which the duration ranges from 13 days (NN method) to 125 days (GK method); GK methods in this case possibly overestimate the time span, due to the complex features of the sequence (Figs. 8a, 8b, 9e, 9f) that exhibits a decrease and recover of seismicity after about one month from the mainshock.

Remarkably, the application of Eqs. 7 and 8 proposed by Gentili and Bressan (2008) is essentially a window method, with parameters optimised to the specific region; therefore, we might expect a better fit with GK and U, rather than with NN. Still, the detailed comparative analysis of individual earthquake clusters, manually selected, shows that the aftershocks automatically identified by the NN method compare quite well with those extracted by *ad hoc* data investigation, particularly in terms of spatial extension of sequences (Fig. 9). In particular, the spatial distribution of epicentres extracted based on NN method coincides with the manual one for the M 5.1 2004 earthquake (Figs. 9c and 9d), while for the M 5.6 1998 earthquake the NN cluster includes a few relatively distant events, still within 25-30 km distance from the epicentre (Figs. 9a and 9b). The sequences identified by NN generally end up earlier than the manually selected ones (about 50-60 days shorter), basically due to the use of the fixed restrictive threshold log η_0=-5.0. As shown in Fig. 5, by increasing the threshold distance log η_0 from -5.0 up to the automatic threshold -4.1, an increasing number of far (both in space and time) earthquakes could be included in the sequences, most of which evidently belong to background seismicity. The performed comparison supports the appropriateness of the NN method, particularly its application to small and moderate size earthquakes in the North-eastern Region, enabling its generalisation and systematic application to a wide set of seismic sequences, and thus allowing for a detailed characterisation of their space-time properties (e.g. Peresan and Gentili, 2018).

The fit of the extracted sequences to classical models of aftershocks occurrence, namely the Modified Omori Law (Utsu *et al.*, 1995), is examined for the Kobarid 1998 earthquake (the most rich and long sequence). Fig. 10 shows the rate of earthquakes as a function of time for the four compared methods (NN, GK, U, and manual), including two different applications of NN, with automatic and with manually selected threshold η_0. The fit of the data to the modified Omori law is computed by the Zmap software (Wiemer, 2001). From the graph, it is possible to observe the longer duration of the sequence using NN method with automatic threshold. The fitting lines of the window based methods appear quite similar, with p = 0.8 and c close to 0, while NN based methods supply a smaller rate for long times, with p in the range 0.95-0.99 and c in the range 0.04-0.08. The rather good agreement in temporal decay of aftershocks rate, which is observed between manually selected sequences (MAN) and those by window methods, could be explained by the fact that MAN is basically also a window method, extracting all events within the specified space-time window, while NN is not (e.g. see Figs. 3 and 4).

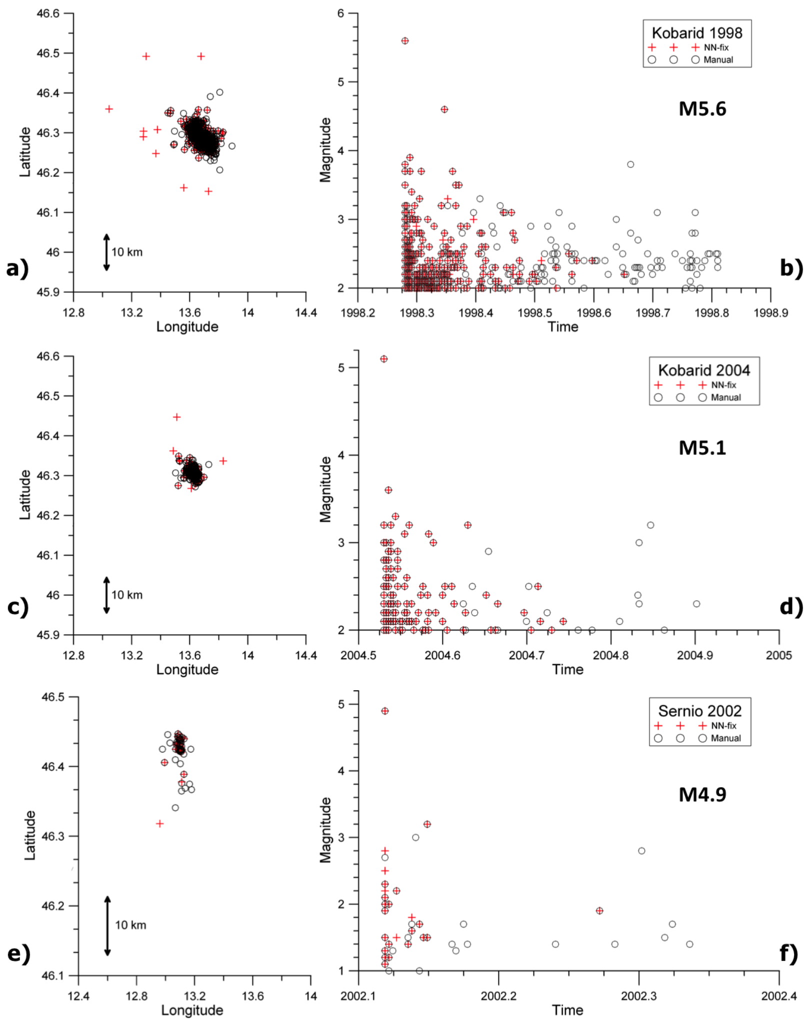

Fig. 9 - Comparison of the sequences identified by the NN method with sequences manually extracted by Gentili and Bressan (2008) for the 1998 and 2004 Kobarid earthquakes, and for the 2002 Sernio earthquake. The plots show the coordinates (left column) and magnitude vs. time (right column) of the events composing the clusters. The sequences were extracted by the NN method with the following criteria: time interval: 1977-2018 scaling parameters: b = 0.9 and d = 1.1; fixed threshold distance log η_0=-5.0. The scales are similar to those in Figs. 7 and 8, to facilitate cross-comparison.

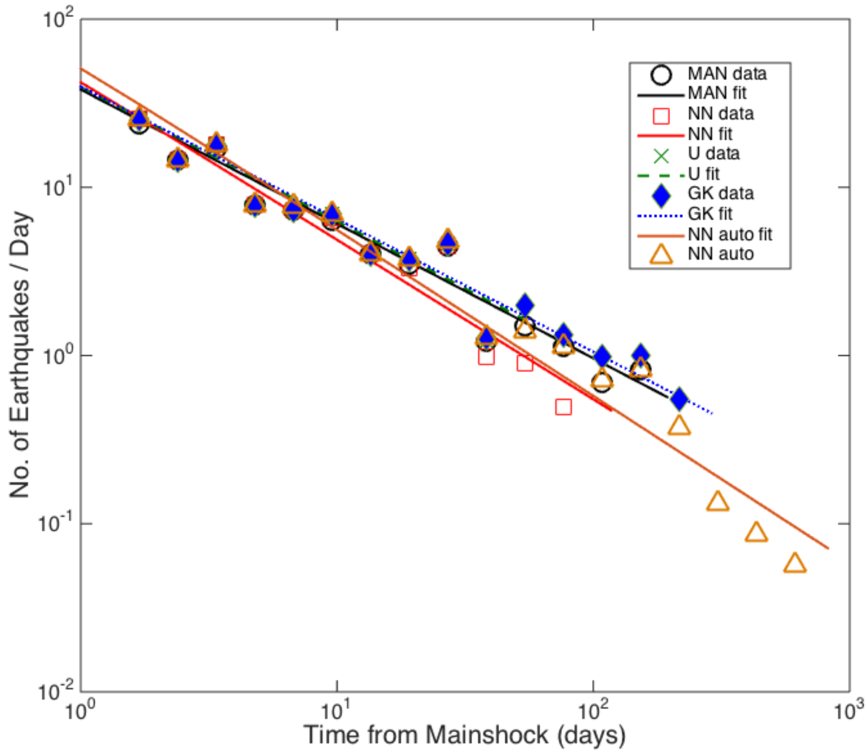

Fig. 10 - Comparison of the temporal features of aftershocks decay, for the clusters identified by the different methods (NN, GK, and U) and for the manually extracted sequence (MAN), considering the *M* 5.6 Kobarid 1998 earthquake. Fits have been obtained for each set of data assuming a modified Omori law. For the NN method, both the application with fixed threshold log η_0=-5.0 (NN) and with automatic threshold log η_0=-4.1 (NN auto) are considered. Only events with $M \geq 2.0$ are involved in the analysis.

4.2. Central Region

In order to compare the performances of the methods in a completely different tectonic setting, the clusters associated with the three largest earthquakes that struck central Italy since 1981, i.e. Colfiorito 1997, L'Aquila 2009, and the Amatrice-Norcia 2016 have been identified by NN, GK, and U methods. Declustering is especially problematic in the Apennines, where different earthquake clusters occur very close in space and time and have a typically elongated distribution of epicentres (Fig. 11).

Table 3 summarises the relevant information about the number of earthquakes, maximum distance from the mainshock and duration of the clusters of Colfiorito and L'Aquila sequences. The comparative analysis of individual earthquake clusters (see Fig. 12) shows that the three methods provide quite consistent results. Like in the case of North-eastern Region, the U method tends to underestimate the cluster duration, with respect to GK and NN, in both Colfiorito and L'Aquila cases. For the Amatrice-Norcia case, the declustering results are pretty similar for all methods. The GK and U methods practically coincide as for the number of events, radius and time span (Table 3); this is possibly due to the re-activation of the cluster in November 2016 and in January 2017, which improves U performances by increasing its duration. At this stage, however, we cannot exclude that the Amatrice-Norcia sequence extends beyond the end of the considered catalogue, which possibly causes an underestimation of the duration of the sequences for all methods. Based on the obtained results, the GK method appears more suitable for central Italy with respect to North-eastern Region and only few earthquakes are wrongly associated, while, again, in Colfiorito and L'Aquila case the U method tends to miss events. The NN method provides results that are very similar to GK method, in terms of time series of events; however,

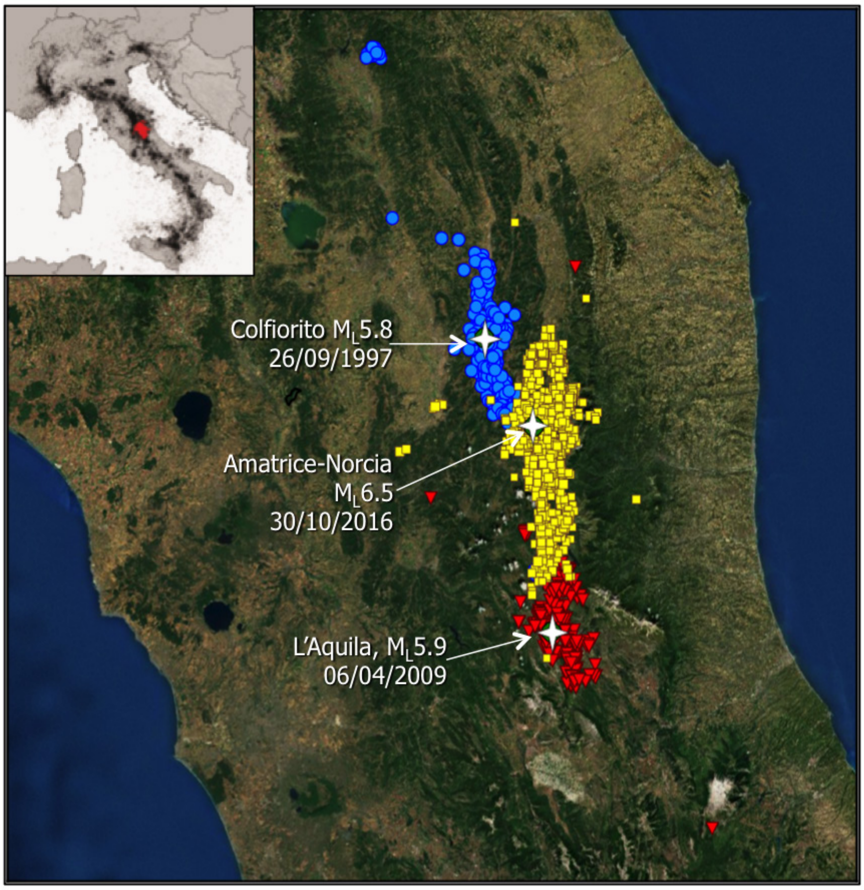

Fig. 11 - Location of clusters identified by the NN method for the three selected sequences: Colfiorito 1997 (blue); L'Aquila 2009 (red) and Amatrice-Norcia 2016 (yellow). White stars mark the epicentre of the main event in each cluster.

due to its statistical formulation, it includes in clusters some sporadic (less than 5%) very distant events, likely belonging to background activity (see left column in Fig. 12 and Table 3). This does not affect the number of earthquakes composing the cluster, where NN and GK methods supply similar results (see Table 3).

We recall that Rotondi *et al*. (2017) already compared the Colfiorito and L'Aquila sequences extracted by NN approach from the ISIDE instrumental catalogue, with those extracted from the historical catalogue CPTI15 (Rovida *et al*., 2016). Basically, they compared results from a longer, but less complete database (CPTI15), with those from a shorter but richer database (INGV). The analysis showed that the clustered component in the distribution of NN distances (e.g. Fig. 2b) is significantly reduced when considering the historical data set, still preserving certain bimodality. Moreover, they found that the use of data with different quality and level of completeness, but with identical parameters and threshold distance, does not affect substantially the association of parent-offspring events, nor the structure of the identified clusters. Basically, once the same parameters and threshold are used, the earthquakes that are reported in both catalogues are consistently identified as parent/offspring events, either using ISIDE or CPTI15 data, in agreement with results obtained by Peresan and Gentili (2018) for north-eastern Italy. Thus, the completeness of the catalogue seems not to be a critical element in NN method application.

Table 3 - Number of aftershocks included in each cluster (Num), maximum distance from the mainshock (Dist_max, in km) and duration (Time, in days) for each of the three selected sequences. Earthquake clusters have been identified by the NN method, considering: a) the automatic threshold distance log η_0=-4.3, and scaling parameters *b*=1.0 and *d*=1.4. The parameters for the GK and U methods application are obtained according to Eqs. 3 to 6.

		Earthquake sequence		
		Colfiorito 1997	**L'Aquila 2009**	**Norcia 2016**
	Mmain	5.8	5.9	6.5
	Mmin	3	3	3
NN	**Num**	266	280	706
	Dist_max	89	104	260
	Time	340	299	125
GK	**Num**	270	283	710
	Dist_max	31	52	59
	Time	340	301	125
U	**Num**	217	251	710
	Dist_max	31	30	59
	Time	72	82	125

4.3. Clusters structure analysis

The NN method allows us not only for the identification of main events and related aftershocks/foreshocks, but it also permits to distinguish aftershocks at subordinate levels (i.e. the aftershocks generated by aftershocks themselves). This property makes it possible to analyse the internal structure of the identified earthquake clusters (i.e. the multi-event clusters) and to classify them according to their topological "tree structure", as proposed by Zaliapin and Ben-Zion (2013b).

The tree structure of clusters may be quite different and can be quantified by different metrics. A possible classification of clusters type is based on the concept of "vertex depth", that is the minimal number *d* of links that connect a given vertex (earthquake) to the "tree root" (the first earthquake in the cluster). Accordingly, the "average leaf depth" <*d*>, that is the vertex depth averaged over the "tree leaves" (vertices with no children), has been defined, which provides a scalar measure characterising the time-oriented tree structure associated with a cluster. A cluster associated with a distributed tree structure, where events are interconnected to form a chain, is defined as "swarm-like sequence" and is associated to relatively high average leaf depth values. A cluster characterised by low values of the average leaf depth, which indicates that most of the events are directly connected to one or a few dominant earthquakes, is defined as "burst-like sequence" refer to Zaliapin and Ben-Zion [(2013b) for further details]. It has been found (Zaliapin and Ben-Zion, 2013b; Daskalaki *et al*. 2014, 2016; Peresan and Gentili, 2018) that the topological properties of the seismic sequences can be related with the relevant tectonic and structural characteristics in the area under examination. We apply this methodology to four sequences, two from each of the considered areas, with the aim to exemplify the differences between earthquake clusters in the Central and North-eastern regions. Moreover, we discuss the structure of the selected sequences, representative for the corresponding areas, to illustrate the possibilities of the NN method.

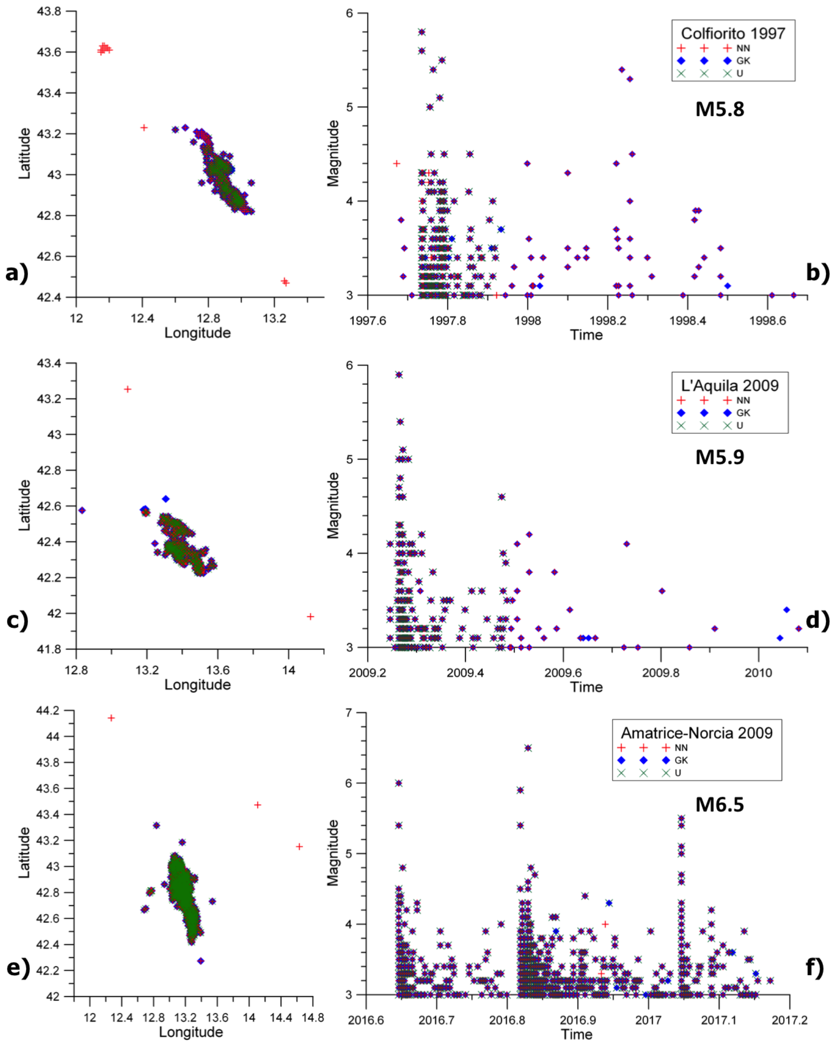

Fig. 12 - Comparison of the clusters associated with the Colfiorito (*M* 5.8, 1997), L'Aquila (*M* 5.9, 2009) and Amatrice-Norcia (*M* 6.5, 2016) earthquakes, as identified by the NN, GK, and U methods: coordinates (left) and magnitude vs. time (right) plots of the events composing the clusters.

Fig. 13 shows the clusters structure associated with the four selected sequences, namely: Kobarid 2004 and Valdobbiadene 2015 in the North-eastern Region, and Colfiorito 1997 and L'Aquila 2009 in the Central Region. The figures show the epicentral distances between the cluster's mainshock and the related events, versus their occurrence time, with links between earthquakes and their respective offsprings (i.e. their NN event). Foreshocks, when present, are marked in green.

The Kobarid sequence, extracted from OGS catalogue, is made up of 264 earthquakes with $M \geq 1.0$, all occurred within a radius of 18 km from the mainshock, and mostly concentrated within a distance of about 5 km. The Valdobbiadene sequence consists of 28 earthquakes, concentrated within a narrow distance < 5 km. We observe that the Kobarid sequence, though generated by a comparatively larger magnitude event, and, therefore, being characterised by a much higher number of aftershocks, has a relatively simple structure, as quantified by the low average leaf depth $\langle d \rangle = 1.15$, which indicates that most of the events are directly connected to the mainshock (burst-like sequence). This value is lower than that obtained for the Valdobbiadene cluster, which has a relatively high average leaf depth <*d*>=3.55, indicating a rather complex internal structure (i.e. swarm-like sequence).

Comparing the two clusters from Central Region, we observe that the Colfiorito sequence has a quite complex structure (Fig. 13c), with an average leaf depth <*d*>=6.81, and develops in multiple generations (Fig. 12b). The L'Aquila sequence, instead, is more concentrated in space (Fig. 12c) and is composed by a larger number of first-generation aftershocks (Fig. 13d), as indicated by a lower value of <*d*>=4.00. We note that in these two selected clusters analysed by the NN method there is a space migration of the secondary shocks, which move away from the epicentre of the mainshock; this is highlighted by the vertical development of the tree structure (Figs. 13c and 13d). Moreover, after a period of decreasing seismicity, a reactivation is observed, that is a second strong event with its own tree structure. These appear to be common features for major earthquakes in the Central Region, confirmed by the complex Amatrice-Norcia sequence started in August 2016. Remarkably, the considered sequences in the Central Region display several foreshocks (Figs. 13c and 13d), in rather good agreement with earlier findings by Daskalakis *et al*. (2016), whereas no foreshocks are identified for the two clusters in the North-eastern Region.

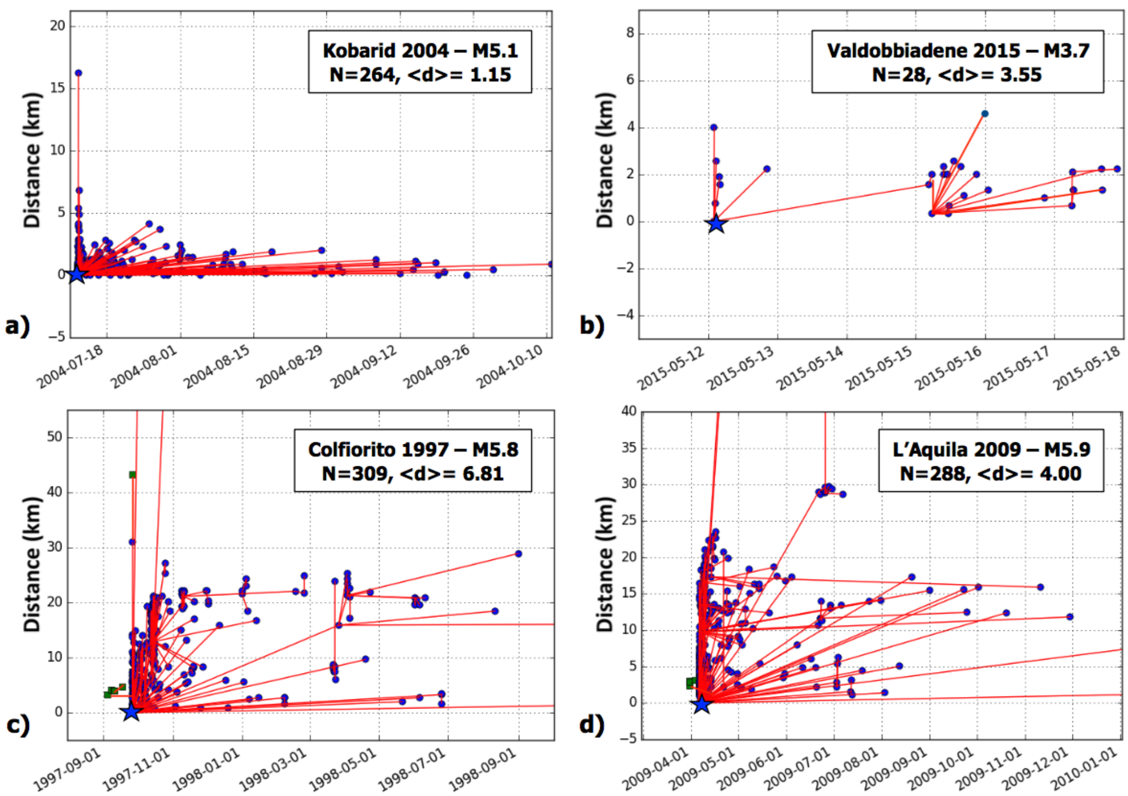

Fig. 13 - Structure of seismic clusters identified using the NN method and associated with the four selected sequences: Kobarid 2004 and Valdobbiadene 2015 earthquakes (North-eastern Region), Colfiorito 1997 and L'Aquila 2009 (Central Region). The epicentral distance (in km) between the mainshock and earthquakes forming the cluster is plotted vs. the corresponding origin time. The red segments link each event to its NN event; foreshocks are marked in green. The blue star marks the mainshock. The number N of events forming each cluster is provided along with its corresponding average leaf depth <*d*>. Clusters were identified considering M_{min}=1.0 in North-eastern Region and M_{min}=3.0 in Central Region.

5. Discussion and conclusions

In this paper, we compared the performances of different cluster identification approaches in two regions characterised by different tectonic regime: north-eastern Italy and western Slovenia (North-eastern Region), characterised by a compressional and shear regime, and the Central Region, where extension mechanisms prevail. In particular, we compared NN approach with two well-known window based methods, namely GK and U methods. The main differences between the NN and the window-based methods are basically two.

The first one is that NN has a soft parametrisation, while window methods require detailed *ad hoc* calibration of parameters. This affects the performances of window-based methods if they are not calibrated for the study area. The GK method, for instance, supplies good performances in central Italy in terms of spatial cluster extension, while it fails in the North-eastern Region, where cluster have a smaller extension. The U method, vice versa, supplies good performances in terms of cluster spatial extension, but it fails in cluster duration estimations, not providing an efficient declustering of catalogues, as the presence of aftershocks is still evident after declustering. This problem is overcome by NN method, because it is data-driven and automatically adapts to different seismicity characteristics.

The second basic difference is that window-based methods eliminate all events within a given space-time window from the catalogue, creating evident gaps in declustered catalogues after major events, while NN method does not alter the features of the inhomogeneous and possibly non-stationary background seismicity, which are relevant for several studies.

Even if the NN, due to its statistical formulation, may in some cases include in clusters some sporadic (less than 5%) very distant events, likely belonging to background activity, it appears more effective in identification and characterisation of earthquake clusters, with respect to window-based methods. In addition, the NN method allows performing an analysis of the internal structure of the cluster to distinguish aftershocks at subordinate levels. It emerges that the clusters' complexity is region-dependent, in good agreement with earlier studies (e.g. Zaliapin and Ben-Zion, 2013b; Peresan and Gentili, 2018). Central Italy clusters, together with the cluster in the eastern part of North-eastern Region, in fact, turn out to be more complex than the ones in western Slovenia. Sequences in the Central Region, in particular, are characterised by the presence of several foreshocks, subsequent reactivations and space migration of the secondary shocks, which move away from the epicentre of the mainshock. This pattern could be physically explained, among the others, by stress-transfer, as it happened during the Amatrice-Norcia sequence started in 2016 (e.g. Papadopoulos *et al*., 2017).

Acknowledgments. We are grateful to I. Zaliapin for providing the code for nearest-neighbour analysis. We are also indebted to R. Rotondi and E. Varini for their valuable contribution and discussions during the preparation of the manuscript. We are especially grateful to two anonymous reviewers for their positive and constructive comments. The research presented in this paper benefited from funding provided by L.R. 19/2000 (year 2016) and by Protezione Civile della Regione Autonoma Friuli-Venezia Giulia.

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