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Distribution of seismicity before the larger earthquakes in Italy in the time interval 1994-2004

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Abstract

The Region-Time-Length (RTL) algorithm has been applied to different instrumental catalogues to detect seismic quiescence before medium-to-large earthquakes in Italy in the last two decades. RTL performances are sensitive to the choice of spatial and temporal parameters. The method for automatic parameters selection developed by Chen and Wu has been applied to 12 Italian earthquakes with magnitude greater than 5. The limits of the method in constructing maps of seismic quiescence before the earthquake are demonstrated, and a simple improvement is proposed. Then a new technique, namely RTL_{surv}, is proposed for routine surveys of the Italian seismicity. RTL_{surv} has been applied to all the earthquakes with magnitude greater than 4 in the Italian area in the time interval 1994-2004; 4 different sub-areas have been identified, with different characteristics in the level of recorded seismicity. One sub-area – Tyrrhenian Sea - was characterized by a too low level of recorded seismicity for the application of the method. In the other three sub-areas a seismic quiescence was detected before at least the 66% of the earthquakes with magnitude greater or equal to 4 and all the earthquakes with magnitude greater than 5.

1. Introduction

Temporal seismic observations have shown trends of seismic quiescences and foreshock activation preceding large events. Many studies focussed on the quiescence occurring during the phase of seismic energy accumulation before moderate and large earthquakes (Scholz 1988, Wyss and Habermann 1988, Wiemer and Wyss 1994), or on the increase of seismicity (Bufe and Varnes, 1993, Brehm and Braile 1998). The RTL analysis is a statistical method developed by Sobolev and Tyupkin (1996,1997) to detect seismic anomalies preceding isolated large earthquakes.

The RTL has been previously applied to large earthquakes in Kamchatka and Caucasus (Sobolev and Tyupkin 1997, 1999, Huang, 2004), Greece (Sobolev et al. 1997), Japan (Huang and Sobolev 2002, Huang et al. 2001, Huang and Nagao 2002, Huang 2004, 2006), Turkey (Huang et

al. 2002, Huang 2004), Taiwan (Chen and Wu 2006) and China (Jiang et al. 2004, Rong and Li, 2007). Using this technique, earthquakes in Italy have been studied by Di Giovambattista and Tyupkin (1999, 2000, 2004) and by Gentili and Bressan (2007).

In this paper, I present new results for the Italian area, analyzing the medium-to-large earthquakes of two catalogues of instrumental seismicity, the first one compiled at the national scale, and the second one referred to NE Italy (see section 3). A preliminary analysis has been done on M>5 earthquakes using the method for the automatic parameters calibration developed by Chen and Wu (2006). In this paper, I analyze the space of the parameters to show how their choice influences the spatial mapping of RTL before the earthquake. A simple improvement of the Chen and Wu method is then proposed.

The choice of the time window to perform RTL mapping is one of the most critical points of the method. It is generally done a-posteriori (e.g. Di Giovambattista and Tyupkin, 2000, Huang and Sobolev, 2002), selecting a time window where RTL function for the examined earthquake assumes low values. In this paper, I propose a new method for routine surveys of the Italian seismicity, named RTL_{surv}; it takes into account the seismicity of the last years before a predefined time, without an ad hoc choice of the time window.

This survey has been applied to all the M>4 earthquakes of the national and regional catalogues in the time period 1994-2004. The performance of the method in terms of quiescence detection and spatial location of the anomalies has been evaluated with respect to earthquake magnitudes.

2. The RTL algorithm and its improved versions

The RTL algorithm was originally proposed by Sobolev and Tyupkin (1996) and it has been described in detail elsewhere (see e.g. Di Giovambattista and Tyupkin, 2004). Briefly, it represents

the deviations from the background seismicity. Quiescence is outlined by a decrease of an RTL function, and activation of seismicity by an increase of RTL.

The RTL value at a given test site (x, y) at time t, is defined as the product of the epicentral function R, the temporal function T and the source-site function L, divided by their standard deviations (eq. 1).

$$RTL(x,y,t) = \frac{R(x,y,t)}{\sigma_R} \cdot \frac{T(x,y,t)}{\sigma_T} \cdot \frac{L(x,y,t)}{\sigma_L} \tag{1}$$

These functions are defined as:

$$R(x,y,t) = \sum_{i=1}^{n} \exp\left(-\frac{r_i}{r_0}\right) - R_s(x,y,t) \tag{2}$$

where r_i is the distance between the test site (x, y) and the ith earthquake, $2r_0$ is the search distance and the summation is performed on the n events considered in the time window (t-$2t_0$, t), having magnitude in the interval (M_{min}, M_{max}), with M_{min}= M_c, the level of the catalogue completeness.

In the temporal term

$$T(x,y,t) = \sum_{i=1}^{n} \exp\left(-\frac{t-t_i}{t_0}\right) - T_s(x,y,t) \tag{3}$$

t_i is the time of occurrence of the events preceding the time of the forecast. Finally, the source-site function is

$$L(x,y,t) = \begin{cases} \sum_{i=1}^{n} \left(\frac{l_i}{r_i}\right) - L_s(x,y,t) & if \quad r_i > \varepsilon \\ \sum_{i=1}^{n} \left(\frac{l_i}{\varepsilon}\right) - L_s(x,y,t) & if \quad r_i \le \varepsilon \end{cases} \tag{4}$$

where ε is the accuracy of the epicenter location and l_i is the size of the source of the selected earthquakes; l_i is usually calculated from empirical relationships between earthquake magnitude and source size. R_s, T_s, and L_s are linear trend corrections.

The RTL function is calculated after declustering the earthquake data set.

Various improvements of the method or different interpretations of the results have been proposed. In Jiang et al. (2004) and Chen and Wu (2006), both decreases and increases of RTL are considered earthquake precursors, while for most other authors (see e.g. Huang and Sobolev 2002) only a decrease (seismic quiescence) is considered a reliable precursor.

One of the open problems in the application of the method is the choice of the free parameters r_0, t_0 and M_{max}. Huang (2006) on the large Tottori earthquake (M=7.3) and Gentili and Bressan (2007) on a set of moderate earthquakes in NE Italy and Western Slovenia, show that the results are stable for a large range of chosen parameters. Chen and Wu (2006) propose a method for the choice of the most stable value of r_0 and t_0, described in detail in the following. In some recent papers, no M_{max} is imposed, to avoid the introduction of potential artificial changes by the two cutoff magnitudes M_{min} and M_{max} (Huang and Sobolev, 2002, Huang 2004, 2006, Chen and Wu, 2006), or because the M_{max} is demonstrated to not influence the results (Gentili and Bressan, 2007). In previous papers $M_{max} \approx M_{seq} - 2$, where M_{seq} is the magnitude of the tested main shock (Sobolev and Tyupkin 1997), or it is set to a given value, like Di Giovambattista and Tyupkin (1999, 2000, 2004), who set M_{max}=3.8 independently of the magnitude of the tested mainshock. In this paper, I exclude M_{max} from the RTL calculation.

Another open problem is how to map RTL in space, in order to detect the seismic quiescence zone. The region in the neighborhood of the epicenter (its dimension changes from author to author, ranging from 150x250 km in Di Giovambattista and Tyupkin (2004) to 1900x1800 km in Huang et al. (2001)), is sampled by a grid, and, for every node of the grid, the RTL is computed for the same time window containing the minimum value of the RTL at the epicenter of the analyzed earthquake. The value mapped is in some cases the minimum of the RTL in the time window (RTL_{min} - see e.g. Sobolev 2000, Di Giovambattista and Tyupkin 2000 and 2004). In most recent papers, the Q parameter is mapped, which is defined as the mean of the RTL in the considered time window (Huang et al. 2002, Huang 2004, 2006). In both cases, this analysis must be done a-posteriori, when the position of the epicenter of the earthquake is known. This is a

drawback, since it lowers the interest of RTL as earthquake predictor. Section 4.3 describes the method proposed in this paper to solve this problem.

3. Data-set pre-processing

Two earthquake catalogues have been used in this paper, pertaining to the regional and national scale. The first one is the regional catalogue released by the Seismic Network of Northeastern Italy, managed by the Seismological Research Center (CRS) of OGS - National Institute of Oceanography and Experimental Geophysics. The catalogue (hereinafter defined as NEI catalogue) reports 16200 events with M>0 from May 1977 (Fig. 1a). A full description of the characteristics of the monitoring is reported in Priolo et al. (2005), and the list of events located using HYPO71 (Lee and Lahr, 1975) is public and available on the web site http://www.crs.inogs.it/bollettino/RSFVG/RSFVG.en.html. The magnitude adopted in this catalogue is the duration magnitude obtained using the Rebez and Renner (1991) formula. The mean location uncertainty is 1.5 km.

<Figure 1 here>

The second catalogue covers the whole country, and it is the one proposed by Lolli and Gasperini (2006) (L&G catalogue). It is a compilation obtained by integrating with uniform criteria different catalogues, namely the PFG catalogue (Postpischl, 1985) that reports macroseismic and instrumentally derived records from 1000 to 1980, the CSTI catalogue (CSTI WorkingGroup, 2001, 2004; instrumental seismicity from 1981 to 1996), the CSI catalogue (Castello et al., 2005; earthquakes in 1981-2002) and two years (2003-04) of instrumental bulletins of the Istituto Nazionale di Geofisica e Vulcanologia (INGV) available at site http://legacy.ingv.it/~roma/reti/rms/bollettino. The resulting catalogue (Fig. 1b) reports 64200 events with M>0 from January 1960 to December 2004 and can be downloaded by anonymous ftp at the address: ibogfs.df.unibo.it and it is in the directory LOLLI/AFT2005 (Lolli and Gasperini,

2006). The magnitude listed is local magnitude. The mean location uncertainty is 7.5 km (Lolli and Gasperini 2003).

3.1 Declustering

RTL applies to declustered catalogues, where both foreshocks and aftershocks are removed. In order to decluster the L&G and NEI catalogues, I have applied and compared the performances of two alternative algorithms: that by Knopoff et al. (2000) and that by Reasenberg (1985), the latter implemented in Zmap software (Wiemer, 2001). The whole Zmap software package can be downloaded from the Swiss Federal Institute of Technology Zurich (ETH Zurich) web pages (http://www.earthquake.ethz.ch/software/).

Knopoff algorithm, for M_L<6.4, is a windowing algorithm for cluster identification. It means that for every event in the catalogue a space time-window is defined and any earthquake within the window is deemed as cluster event. The extension in time and in space of the window depends on the magnitude of the earthquake. In applying the algorithm to L&G catalogue, I used of the original table proposed by Knopoff et al. (2000), extended to smaller magnitudes as in Pace et al. (2006) in Italian catalogues declustering:

$$\begin{aligned} Log(T) &= 0.725M_L - 2.007 \\ Log(D) &= 0.347M_L - 0.567 \end{aligned} \tag{5}$$

where T and D are the time and space windows expressed in days and kilometers, respectively, and M_L is the local magnitude. For NEI catalogue declustering, since the listed magnitude is the duration magnitude, I adopted the relationships obtained by Gentili and Bressan (2008) for the area covered by the catalogue:

$$\begin{aligned} Log(T) &= 0.33M_D + 0.42 \\ Log(D) &= 0.41M_D - 1 \end{aligned} \tag{6}$$

where M_D is the duration magnitude. For simplicity, since the algorithm is the same for NEI and L&G catalogues, even if the relations (5) and (6) are different, this algorithm will be referred in the following simply as modified Knopoff algorithm.

The Reasenberg algorithm defines a seismic sequence as a chain of events linked each other by spatial and temporal windows. The window's extension in time and space depends on a set of parameters and on the seismic moment of the largest and the most recent event. In particular, the spatial extent of the mainshock is taken coincident with its source dimension; that is (Kanamori and Anderson 1975):

$$r = \left(\frac{7}{16} \frac{M_0}{\Delta\sigma} \right)^{1/3} \tag{7}$$

where $\Delta\sigma$ is the stress drop, assumed 3MPa for all the earthquakes, and M_0 is the seismic moment. The spatial extent of the most recent event is its source dimension scaled by a parameter Q. A location uncertainty is considered in the calculation. The temporal window is defined as a function of the time *t* after the beginning of the sequence:

$$\tau = \frac{-\ln(1-P)t}{10^K} \tag{8}$$

where *P* is related to the probability of observing one or more events and *K* is related to the mainshock magnitude. An upper and lower limit for τ (τ_{min} and τ_{max}, respectively) are input parameters. Since the characteristics of the catalogues and of the seismicity in California, for which the algorithm was developed, are different, I tested the declustering using both the default parameters (Q=10, τ_{min}=1, τ_{max}=10, P=0.95) and the ones proposed for Italy by Lolli and Gasperini (2003) (Q=20, τ_{min}=2, τ_{max}=10, P=0.99). Lolli and Gasperini (2003) double the spatial extent of the window.

I used the following conversion rule between local magnitude and seismic moment (Lolli and Gasperini 2003, Gasperini and Ferrari 2000):

$$Log_{10}(M_0) = 1.22 M_L + 17.7 \tag{9}$$

In order to find a relation between duration magnitude and seismic moment valid for Northeastern Italy, I used the data of moment magnitude listed in Franceschina et al. (2006) and Bressan et al. (2007) obtaining the following regression (see Fig 2):

$$\begin{aligned} Log_{10}(M_0) &= 1.3M_D + 9.3 \\ \sigma(Log_{10}(M_0)) &= 0.3 \end{aligned} \tag{10}$$

where σ(.) is the standard deviation.

<Figure 2 here>

In Fig. 1a and b the cumulative number of earthquakes with magnitude >0 for the two catalogues are compared with their declustered version after applying (i) the declustering obtained by applying Knopoff et al. (2000) algorithm (ii) the Reasenberg algorithm with default parameters (iii) the Reasenberg algorithm with Lolli and Gasperini parameters.

The NEI catalogue (Fig. 1a) presents a clear increase on the number of earthquakes corresponding to the seismic sequences of the 12th April 1998 M_D=5.6 and the 12th July 2004 M_D=5.1 Kobarid earthquakes. A smaller increase of the cumulative number of earthquakes can be seen also due to the seismic sequence of the 1st February 1988 M_D=4.1 Mena earthquake (for more details on the sequences in this area, see Gentili and Bressan 2008). All the declustering procedures were able to eliminate these increases. In addition, in both the original and declustered catalogue it is possible to see a decrease in slope of the curve in 1988. This is due to the change of the data acquisition method. The seismic data acquisition before January 1, 1988 was analog, all the data were collected and there was no triggering algorithm. After this date, the seismicity was acquired with digital signal processing; the signal was acquired when the ratio (Short Term Average)/(Long Term Average) passed a given threshold. Therefore, smaller magnitude earthquakes were neglected (Marcellini and Milani 2003). The seismicity recording was interrupted on December 3, 1990 and started again on May 21, 1991 (Gentili and Bressan 2007). The interruption is marked by two dashed lines. The main difference in the results of the declustering procedures is in the number of events in the declustered catalogues. While modified Knopoff algorithm removes about 2800 events

out of the 16200 with M_D>0 from the catalogue, Reasenberg algorithm removes 4800 and 5800 events using default and Lolli and Gasperini parameters, respectively. In order to understand which is the best declustering procedure, I verified their performances on two seismic sequences and a swarm, whose events are listed in Bressan et al. (2007). I found that the best procedure is the Knopoff (2000) algorithm. The mainshocks of the sequences are the 12th April 1998 M_D= 5.6, Kobarid and the 14th February 2002 M_D= 4.9 Sernio Mountain earthquakes. The swarm was composed of three sequences whose mainshocks were the 27th January 1996 M_D= 3.5, the 27th February 1996 M_D= 3.8 and the 13th April 1996 M_D= 4.3 Claut earthquakes. The results are the following:

- Knopoff (2000) algorithm correctly removes from the catalogue all the dependent earthquakes of the seismic sequences; all the mainshocks are correctly recognized.
- Reasenberg algorithm using default parameters fails in removing two aftershocks in Sernio sequence and one in the last sequence of the Claut swarm. In addition, it wrongly removes the 13th April 1996 M_D= 4.3 Claut mainshock from the catalogue.
- Reasenberg algorithm using Lolli and Gasperini parameters fails in removing two aftershocks in Sernio sequence. In addition, it wrongly removes the 13th April 1996 M_D=4.3 Claut mainshock from the catalogue.

The same analysis was performed on the L&G catalogue (see fig 1b). The L&G catalogue presents a remarkable increase of the number of earthquakes due to the cluster of earthquakes in Umbria-Marche started on 26th September 1997. Minor increases can be seen corresponding to the seismic sequence of the 6th May 1976 M_L=6.1 Friuli earthquake, of the 29th April 1984 M_L=5.2 Gubbio/Valfabbrica earthquake and of the 6th September and 31st October 2002 M_L=5.6 Palermo and M_L=5.6 Molise earthquakes. All the declustering procedures were able to eliminate these increases. A change of slope of the cumulative number of earthquakes can be seen around the year 1995 in both the original and the declustered catalogues. This is due to a change in the network acquisition system in 1994 (Lolli and Gasperini 2003) and an increase of the number of seismic

stations in 1996 that improved the detection capability of some Italian regions (e.g. in Sicily: see Di Giovambattista and Tyupkin, 2004). In this case also, the main difference among the declustered catalogues is the number of earthquakes. While the modified Knopoff algorithm removes about 13400 events out of the 64200 with $M_L>0$ from the catalogue, Reasenberg algorithm removes 19200 and 26300 events using default and Lolli and Gasperini parameters, respectively. In order to make a comparison between declustering the methods, I verified their performances on Umbria-Marche seismicity in 1997 using the data from Selvaggi et al. (2002) in order to have a more accurate location of the earthquakes ipocenters; the dataset was composed of 646 earthquakes. The modified Knopoff algorithm detects 15 independent events, recognizing all the distinct ruptures of fault segments, while Reasenberg algorithm recognized 8 and 4 independent events using default and Lolli and Gasperini parameters, respectively. These results and the final choice of modified Knopoff algorithm are in agreement with the ones obtained by Pace et al. (2006) on the same data.

3.2 Completeness

The magnitude of completeness has been evaluated for the two catalogues by using the Entire Magnitude Range method (EMR) (Woessner and Wiemer 2005) and a bootstrapping method for uncertainties evaluation. The software adopted was Zmap. The analysis was performed on declustered catalogues, since during large clusters or aftershock sequences a different policy of recording with respect to standard background seismicity is generally applied (see also Schorlemmer and Woessner 2008). The magnitude of completeness for NEI catalogue is M_D=1.9±0.4 using modified Knopoff 2000 declustering method, 2.3±0.07 and 2.3±0.05 using Reasenberg method with standard and Lolli and Gasperini parameters, respectively. The magnitude of completeness for L&G catalogue is M_L=2.1±0.09 using modified Knopoff 2000 declustering method, 2.1±0.1 and 2.1±0.09 using Reasenberg method with standard and Lolli and Gasperini parameters, respectively.

However, the study of the whole catalogue hides the changes in time and space of M_c, depending on the seismic network available. Fig. 3 shows the changes in time of M_c for both catalogues, calculated using Zmap software. It is possible to notice an increase of M_c for NEI catalogue in the time interval 1985-1990 and a successive stabilization on larger values, due to the change in network acquisition system (see also section 3.1). The L&G catalogue is characterized by a general decrease of the completeness magnitude from 1986 to the end of 2002. An increase of M_c is clearly detectable in 2003, when the instrumental bulletin data were merged with pre-existing catalogues.

<Figure 3 here>

In order to manage homogeneous catalogues, both in terms of network structure and of acquisition system, without interruptions in data recording, in a mostly overlapping time period, the analysis is performed for NEI catalogue from 21st May 1991 until the end of 2004 and for L&G catalogue from 1st January 1986 until the end of 2004.

3.3 Selection of target events

The RTL analysis needs a seismicity recording time interval, before the target event, in order to become stable. The duration of this time interval depends on the earthquake rate in the region under study and on the completeness magnitude of the catalogue. For studies in Italy, this time interval ranges between 6 years for the 1996 M_D=4.3 Claut earthquake (Gentili and Bressan 2007) to 12 years for the 2002 M_L=5.6 earthquake (Di Giovambattista and Tyupkin, 2004). Table 1 shows all the earthquakes in Italy and in the surrounding regions with M>5, from 1st January 1994 to 31st December 2004, listed in NEI and L&G catalogue; the 14th February 2002 M_D=4.9 earthquake is analyzed as a M_L>5 earthquake, even if L&G catalogue lists it as M_L=4.9, because its local magnitude is considered in this paper to be M_L=5.1 in accord with Franceschina et al. (2006).

All the earthquakes analyzed are preceded by a time interval of at least 7 years of available data in the catalogue adopted for RTL analysis (see later).

In order to apply the RTL method for retrospective earthquake forecasting with reliable results, the following selection rules have been applied:

1. In cases of swarms or seismic sequences only the first shock with magnitude greater than 5 is considered.
2. Deeper earthquakes (deeper than 200 km earthquakes) are not analyzed.

The first choice is made because RTL has been developed for detecting seismic anomalies preceding isolated large earthquakes. A quiescence preceding a large earthquake precedes also its seismic sequence or the other earthquakes composing a seismic swarm. RTL does not allow a discrimination between one or more shocks following a seismic quiescence. According to point 1, six Umbria-Marche earthquakes and the 1st November 2002 Molise earthquake (in italic in Table 1) are rejected from the target events list. The second choice is done to avoid confusion between shallower seismicity quiescence and deeper events; this choice causes the rejection of other 3 earthquakes from the target events list: the M_L=5.7 5th January 1994 and the M_L=5.4 18th May 1998 South Tyrrhenian Sea earthquakes and the M_L=5.3 5th May 2004 Aeolian Islands earthquake. The 12 earthquakes analyzed are listed in boldface in Table 1. In order to avoid artifacts due to the mixing of the two different kinds of magnitude listed in NEI and L&G catalogues, which can cause fake quiescence patterns (see also Habermann 1987 and Wyss 1991), the analysis for each earthquake is done using only the catalogue that better covers the epicentral area. In particular, Sernio Mountain and the two Kobarid earthquakes are analyzed by using NEI catalogue, while for the other 9 earthquakes L&G catalogue is adopted.

4. RTL analyses

In order to analyze the parameter dependence of RTL, the algorithm has been retrospectively tested on M>5 earthquakes, using both the Chen and Wu (2006) method and standard values. The comparison has been performed also with results in the literature, when available. The parameters' choice affects both the duration of the detected seismic quiescence and the spatial extension of quiescence area. A simple improvement of the Chen and Wu (2006) method, that reduces the spatial extension of quiescence area, is proposed. In addition, a survey method for the whole Italian area, based on RTL, is presented.

4.1 Retrospective forecasting of M>5 earthquakes

The RTL has been calculated at the epicenter of the 12 earthquakes listed in bold in Table1. When L&G was the reference catalogue, the relation adopted by Di Giovambattista and Tyupkin (1999) (Papadopoulus and Voidomatis, 1987) for l_i evaluation has been taken:

$$Log_{10}(l) = 0.44M_L - 1.289 \quad (11)$$

where l is the size in km of the seismic source and M_L is the local magnitude. The accuracy of the epicenter location was given as ε=7.5 km (Lolli and Gasperini 2003). The analysis started on 1st January 1986 and lasted until midnight of the day before the considered mainshock.

If the NEI catalogue was used, an additional conversion rule was invoked before applying equation (11):

$$M_L=1.2M_D-0.73 \quad (12)$$

where M_L is the local magnitude and M_D is the duration magnitude (Gentili and Bressan 2008). The accuracy of the epicenter location adopted was the mean of value of horizontal errors given by the location procedure (HYPO71) given as ε=1.5 km. The time interval considered was from 21st May 1991 to midnight of the day before the considered mainshock.

In order to avoid artifacts due to heterogeneities in the completeness threshold in the catalogues in different regions of Italy, M_c has been evaluated for each earthquake, by the EMR method implemented in Zmap software, using a search radius of 100 km from the epicenter, by analyzing also its variation in time, from the "starting date of the catalogue" (1st January 1986 for the L&G catalogue, 21st May 1991 for NEI) until the date of the studied events. The highest value reached by M_c has been set as minimum magnitude for computation. The M_c adopted for each earthquake is listed in Table 2.

The t_0 and r_0 parameters have been estimated using the search method developed by Chen and Wu (2006):

- The t_0 parameter was varied in the range $[t_{0min}, t_{0max}]$ with step Δt_0.
- For each value $\hat{t}_0$ of t_0, a set of RTL($\hat{t}_0$, r_0) was calculated, varying the value of r_0 in the range $[r_{0min}, r_{0max}]$ with step Δr_0.
- The RTLs were considered two by two and their correlation coefficients at a significance level of 0.05 (Bendat and Piersol, 2000) were evaluated.
- The percentage $p(\hat{t}_0)$ of correlation coefficients over a given threshold θ was evaluated.
- The value of t_0 corresponding to the peak value of the distribution of $p(t_0)$ was selected as the best one.
- An analogous approach has been applied to r_0 parameter.

The method finds the values of the parameters for which the RTL is more stable, eliminating or reducing anomalies correlated with the choice of parameters (Chen and Wu 2006).

The tested time t_0 has been varied in this paper from 0.2 to 2 years with steps of 0.1 year; the tested radii from 15 to 80 km with steps of 5 km. Accordingly with Chen and Wu (2006), the threshold θ has been set equal to 0.8 for t_0 estimation and equal to 0.5 for r_0 estimation. Different thresholds have been used because changes in t_0 influence the RTL more than changes in r_0 (see also Huang, 2004, 2006 and Gentili and Bressan, 2007). The results are summarized in Table 3. The

values of t_0 range from 0.4 to 1.4 years, while r_0 ranges from 15 to 65 km. For most sequences the estimated coefficient t_0 has more than the 50% of correlation coefficients greater than 0.8 and the estimated r_0 has more than 65% of the correlation coefficients greater than 0.5.

<Figure 4 here>

In Fig. 4 the obtained RTL is shown by a solid thick line. The RTL obtained with fixed parameters (r_0=30 km, t_0=0.5 years, used by Di Giovambattista and Tyupkin (2004) for Palermo earthquake) given in literature is plotted too (thin grey line in Fig. 4). It is possible to see that the results in Fig. 4 for different choices of the parameters are generally qualitatively similar, even if the duration of quiescence and the minimum value reached by RTL may change. Three other tests have been done in order to verify the stability of the method.

The first test is done by changing the magnitude threshold used for calculation; the test is repeated for both magnitudes greater than the completeness magnitude and for smaller magnitudes, under the hypothesis that the completeness magnitude is overestimated. In Table 4 the maximum and the minimum magnitude threshold for which the quiescence is detectable are listed, together with the completeness magnitude. Tests on the Reggio Emilia earthquake are not done, because no seismic quiescence is detected. For most earthquakes, the minimum magnitude is 0 (with no magnitude threshold). The only case in which it is larger than 0 is Merano earthquake; however, also in that case, the minimum magnitude is well below the completeness magnitude. The maximum magnitude coincides in all cases with the maximum magnitude for which the number of earthquakes used to calculate RTL is not too small to supply reliable results. I have considered the RTL to be reliable if at least 50 earthquakes are used for calculation. The previous test outlines a good stability of the RTL also for different choices of completeness magnitude.

The second test is done to verify the performances of RTL using the L&G catalogue in the NE area. The three M>5 earthquakes in the area, analyzed by NEI catalogue, present a well defined seismic quiescence some years before (Kobarid 1998, Fig. 4d) or immediately before the mainshock (Sernio Mountain and Kobarid 2004 – Fig. 4 g and 4 m) that is stable under a wide interval of

magnitudes (see Table 4) but also t_0 and r_0 values (see Table 3 and section 4.2). The same earthquakes are analyzed by applying Chen and Wu procedure for the choice of r_0 and t_0 parameters but using the L&G catalogue. The results are shown in Fig. 5. Comparing figures 4d, 4g and 4m with the corresponding figures 5a, b, c it is possible to see that the RTL applied to the L&G catalogue is not able to detect seismic quiescence in Sernio Mountain case (Fig. 5b); it detects a seismic sequence in Kobarid 1998 case but very far from the time of the mainshock (Fig. 5a); only in Kobarid 2004 case (Fig. 5c) are the results qualitatively similar. This is probably due to inaccuracy of earthquake location and magnitude determination of national catalogues in NE area, which is not well covered by the national network (a map of the national seismic network can be found in the Centro Nazionale Terremoti of the Istituto Nazionale di Geofisica e Vulcanologia – INGV web pages http://www.cnt.ingv.it).

<Figure 5 here>

The last test on RTL stability is done changing the declustering method. In particular, the declustering is performed by using the Reasenberg declustering method with the parameters of Lolli and Gasperini and the same r_0 and t_0 parameters of Fig. 4. The corresponding RTL are shown in the Fig. 6. Using Reasenberg declustering method, the RTL are qualitatively similar to the ones obtained by modified Knopoff method for the most of analyzed earthquakes, with only the exception of the 1998 Calabrian-Lucanian earthquake (Fig 4e and 6e), for which the quiescence preceding the earthquake is less relevant than using Knopoff method (RTL values in the range [-0.7,0]), and 2003 Adriatic sea earthquake (Fig 4l and 6l), where the RTL could be evaluated only for $r_0 \geq 30$ due small number of earthquakes after the declustering.

<Figure 6 here>

Table 5 summarizes the results, in terms of quiescence and successive activation stage duration (when an activation occurred), and of time shift before the analyzed shock, for the RTL calculated using the Knopoff declustering method and the parameters listed in Table 3. If more than one quiescence or activation phase occurred, the last one is considered. Only 3 of the earthquakes

considered present an activation phase after the quiescence. However, 11 of the 12 analyzed earthquakes present a seismic quiescence. The duration of the quiescence ranges from 0.6 years to 3.0 years. The interval between the start of the quiescence to the earthquake is of the order of years, ranging from 0.6 to 4.0 years. This confirms the results already discussed in Sobolev and Tyupkin (1996) and Huang and Sobolev (2002) for which RTL should be considered an intermediate term precursor (range of years) and is not useful as short term precursor (months to weeks range).

Six of the analyzed earthquakes (Reggio Emilia, Umbria Marche, Kobarid 1998, Sernio Mountain, Palermo, Kobarid 2004) have been already studied using RTL with empirical choices of the parameters (Di Giovambattista and Tyupkin, 1999, 2000, 2004, Gentili and Bressan, 2007). Since the parameters here are generally different from the ones adopted in the literature, the catalogues used for the whole of Italy are different (in particular in Lolli and Gasperini catalogue the magnitude is revised) and the declustering method is different, the comparison can be only qualitative.

RTL does not present any quiescence before the Reggio Emilia earthquake neither in this paper (see Fig. 4b) nor in Di Giovambattista and Tyupkin (1999). An activation stage from the last months of 1995 until the earthquake day (15th October 1986) can be seen in Di Giovambattista and Tyupkin (1999), but not in this paper. The RTL curves before Umbria-Marche (Fig. 4c) and the Palermo (Fig. 4h) earthquakes are qualitatively similar to the ones in the literature (Di Giovambattista and Tyupkin 2000 and 2004, respectively), with an RTL decrease followed by a recovery stage before the main shock. Regarding earthquakes analyzed by the NEI catalogue, (Kobarid 1998, Sernio Mountain and Kobarid 2004 - Fig 4d, g, m respectively) the resulting RTL curves are qualitatively similar to the results presented in the literature (Gentili and Bressan 2007), with a quiescence followed by an activation of seismicity preceding the mainshock in the Kobarid 1998 case (Fig. 4d), and a decrease of RTL until the midnight before the mainshock for the Sernio and Kobarid 2004 earthquakes (Fig. 4 g and m).

4.2 Spatial distribution of RTL

The quiescence region has been mapped in this paper by the Q parameter (Huang et al. 2002) i.e. the mean of the value of RTL in a selected time window. In order to avoid noisy results, only values of Q≤-0.5 are considered. The time window chosen for each analysis is listed in Table 6. The completeness magnitude is evaluated for the whole area shown in the map by the EMR method by analyzing also the variation in time. The highest value reached has been used for computation and is listed in the table (column 2). Note that M_c presented in Table 6 is generally larger than the one listed in Table 2, due to the larger area considered in the computation. A first test has been done by using the values selected in the previous section (see Table 3) for the evaluation of RTL at the epicenter of the mainshocks; the radius r_0 adopted (column 4) is compared with the linear dimension of the quiescence zone (column 5). It is easy to see how the area covered by the quiescence is generally larger for larger values of the radius r_0, independently of the earthquake analyzed, while the time t_0 is not influential. This is not surprising, since enlarging the radius of the RTL causes each point to be affected by the influence of a larger area causing a blurring of the map image. In some cases (see e.g. the Merano earthquake) the area characterized by seismic sequence is so large that RTL loses utility for seismic risk assessment. For this reason, the obvious question is whether it is necessary to use such large radii like e.g. for the Merano earthquake, or if with smaller ones it is possible to obtain reliable results.

In this paper I propose two possible approaches to the problem. The first approach consists simply in setting a threshold T on r_0, and considering the r_0 corresponding to the peak value of $p(r_0)$, for $r_0 \leq T$, as the best parameter for RTL mapping. I set the threshold to r_0=30 km, that is the value adopted by Di Giovambattista and Tyupkin (2004) for Palermo earthquake; 30 km is also the minimum radius for which RTL supplies stable results for low seismicity areas like e.g. the Merano earthquake area. The results are listed in column 6 and 7 of Table 6. It is possible to see that the quiescence is still detectable for the same 11 earthquakes for which it was found using the Chen and

Wu method, but in 5 cases the quiescence area extent is smaller. It is particularly interesting in the Merano earthquake case, where the linear dimensions of the quiescence area passes from 800 km to 200 km.

The second approach merges the stability requirements addressed by the Chen and Wu method and the additional requirement that r_0 is as small as possible, in order to reduce the dimension of the quiescence area. The algorithm adopted in this case is the following:

1. The RTL is calculated at the epicenter of the future earthquake, using r_0 and t_0 parameters obtained by Chen and Wu method
2. If a quiescence is detected the analysis time interval is selected (that is one listed in column 3 of Table 6)
3. The r_0 parameter is recursively reduced, maintaining t_0 unchanged, evaluating again the RTL
4. The minimum value of r_0 for which the quiescence is still detectable is selected as the correct parameter for mapping.

This simple method allows study of a quiescence that is stable on a wide range of parameters and on the other side it allows to have smaller quiescence areas. The results are listed in Table 6 (columns 8 and 9) and the corresponding maps are presented in Fig. 7. The linear dimensions of the quiescence regions are smaller than the ones obtained by Chen and Wu method in 91% of the cases and range from 50 km to 450 km.

<Figure 7 here>

All the earthquakes except Reggio Emilia are inside the quiescence zone even if only a few of them coincide with the minimum of Q while in three cases (Umbria Marche –Fig. 7c, Merano – Fig. 7f, Palermo – Fig. 7h) the earthquake epicenters are close to the borders of the quiescence region. This result is coherent with other results in literature (Huang et al. 2001, 2002, Sobolev 2000).

Of the 12 earthquakes with magnitude > 5 in Italy only for the Umbria Marche and Palermo earthquakes is the RTL map supplied in literature (Di Giovambattista and Tyupkin 2000 and 2004,

respectively). For Umbria Marche the time interval for the analysis adopted by Di Giovambattista and Tyupkin is different; they chose the time interval 5th September 1996 - 5th September 1997, that has no overlap with the time period chosen in this paper (2nd July 1995-1st July 1996). The reason for different choice can be ascribed to the fact that the detected minimum in RTL (seismic quiescence) changes its duration and shape depending on the parameters (see Fig. 4c). The area characterized by the quiescence ranges in Di Giovambattista and Tyupkin paper from approximately 42° to 44° in latitude and in longitude from less than 11° to 14.5^{o} and covers Italy from one coast to the other. The earthquake epicenter is approximately at the center of the area. The mapping method they adopted is RTL_{min}. In this work the Q method is adopted and a large quiescence area is evident at lower latitude, with the earthquake epicenter on the northern border of the quiescence area. The latitude range is approximately [41°- 43°] after choosing an r_0 equal to of 35 km or 30 km (see Fig. 8a and b, respectively) and [42°-43°] choosing an r_0 equal to 10 km (see Fig. 7c). In addition, the western coast is not included in the quiescence. With r_0 equal to 30 km or 35 km the extension ranges from 12° to 15° in longitude and with r_0 equal to 10 km 12.5^{o} to 13.5^{o}, not including the eastern coast.

<Figure 8 here>

The map presented by Di Giovambattista and Tyupkin (2004) for Palermo earthquake was obtained in the same time period used in this paper. However only a small study area is analyzed, and the spatial extension of the quiescence areas cannot be compared.

4.3 Development of RTL_{surv}

Previously, quiescence zones had been found for most of the earthquakes analyzed, but the time interval adopted was chosen as the year when the RTL at the epicenter of the earthquake had a minimum. This is an a-posteriori choice that can be done only after that the epicenter is known. In

addition, also the r_0 and t_0 parameters depend on RTL calculated at the epicenter and, therefore, on epicenter position. In this paper, and based on the promising results shown above, I propose a new approach for a continuous survey of the catalogue that can be done before the occurrence of the earthquake.

In developing the proposed method I considered the following facts:

1. Most considered earthquakes are preceded by one or more quiescences.
2. From the start of the quiescence to the earthquake there is a time interval ranging from 0.6 to 4 years (see Table 4). These results are similar to many others in the literature (see Sobolev and Tyupkin 1997, 1999, 2000, Di Giovambattista and Tyupkin 2000, 2004, Huang et al. 2001, 2002, Huang 2006; Chen and Wu 2006, a partial review of previous results can be found in Huang 2004), and therefore can be considered general.
3. Only 1/4 of the analyzed earthquakes present an activation of seismicity, while the 92% present a quiescence. Therefore only the quiescence and not the activation can be regarded as a useful precursor in this study (see also Huang 2004 and references within).
4. Even if the quiescence can be detected for different values of r_0 and t_0, its beginning and its end time are parameter dependent.
5. RTL mapping methods existing in literature need an a-priori choice of the time period to be analyzed. Wrong choices of the period, if RTL_{min} method is adopted, may move the analysis into a time period where there is no quiescence, and supply non-negative values in the area where the epicenter will be. The Q method is even more sensitive to the choice of the time window, because if it contains both the quiescence and a successive activation, negative and positive values of the RTL can cancel each other, supplying positive or null values to the RTL map in the area of the future earthquakes.

The last point seems to indicate a slightly better performance of RTL_{min} instead of Q. However, the advantage of the Q method is that it takes into account the whole analyzed time

period, while RTL_{min} is sensitive to short duration spikes of the signal that can be due to casual fluctuation or inaccuracy in earthquakes locations.

Summarizing all the previous results and considerations I have developed a method that:

1. Considers all the potential times of quiescence before the earthquake
2. Neglects activation phases

The method, named, RTL_{surv}, is calculated at every node of a grid of the investigated area and defined in the following way:

$$RTL_{surv}(j) = \frac{1}{N}\sum_{i=1}^{N} RTL(i,j)\vartheta(RTL(i,j)) \tag{13}$$

where

$$\vartheta(RTL(i,j)) = \begin{cases} 1 & if \quad RTL(i,j) < 0 \\ 0 & otherwise \end{cases}$$

RTL(i, j) is the RTL calculated at node j at time i, RTL_{surv}(j) is calculated at the jth node of the grid and N in the number of data points of RTL in the time interval chosen for the analysis. In this work, a time step of 10 days is chosen. The grid cells are of 10x10 km. In accord with the previous results, the time interval chosen is 4 years long and ends with the time where the forecast starts. The forecast is valid for six months, and then it is repeated. An earthquake is considered corresponding to a quiescence zone if its distance from the nearest quiescence cell is smaller or equal to $2\varepsilon+L/2$, where L is the cell dimension (10 km in this case). In order to automatically avoid inclusion of unstable results in the maps, for each cell j, RTL, and therefore $RTL_{surv}(j)$, is calculated only if at least 50 earthquakes are localized inside a radius of $2r_0$ from the node in the time period from the start of the catalogue until the time of calculation (see also section 4.1). In addition, cells with RTL_{surv}>-0.5 are not considered as quiescence cells (see Section 4.2).

5. Alarms and false alarms

Due to the bad performances of RTL using L&G catalogue in NE Italy (see section 4.1) the analysis in this area has been done by using NEI catalogue. The method has been tested separately on declustered L&G and NEI catalogues on two contiguous regions shown in Fig. 9a. The analysis of the L&G catalogue is aimed at detecting seismic quiescence before the earthquakes with $M_L \geq 4$ and depth <100 km in the time interval 1st January 1994 – 31st December 2004; the analysis of the NEI catalogue is aimed at detecting seismic quiescence before $M_D \geq 3.9$ (corresponding approximately to $M_L \geq 4$ – see equation 12) earthquakes with depth <100 km in the time interval 1st January 1998 – 31st December 2004. The forecast has been done every 6 months and is valid for 6 months or more. The value of the completeness magnitude for L&G catalogue has been set to M_L=2.4 until the end of 2002 and M_L=2.6 for the last two years because the instrumental bulletin has higher completeness magnitude (see Fig. 3b); for the NEI catalogue a completeness value of M_D=2.4 has been adopted (see Fig. 3a).

<Figure 9 here>

One open problem is the choice of parameters r_0 and t_0. For t_0 I choose simply the mean of the values listed in Table 3, that is t_0=0.9 years. Ideally, for the choice of r_0, a method like Chen and Wu one, perhaps with a threshold on the maximum value of r_0, should be applied. However, besides being computationally intensive, this choice would cause different vales of r_0 in different regions of the same map, and not all the points would be weighted evenly. On the other side, selecting the same value of r_0 for large regions, like, e.g., all Italy, engenders some problems. Small values of r_0 can lead to unstable RTL in regions where few earthquakes are recorded, due to the small number of data available. Conversely, large values of r_0 cause a large quiescence area, reducing the value of the method. The performances have been tested for both the L&G and NEI catalogues in the respective analysis areas by varying the value of r_0 from 10 to 30 km with steps of 5 km. The percentage of earthquakes preceded by a quiescence (found earthquakes) with $M_L \geq 4$ is plotted in

Fig. 10a and 11a respectively, and compared with the percentage of quiescence area with respect to the whole area analyzed by the catalogue (Fig. 10b and 11b). An approximately linear increase of the quiescence area with the radius is detected for both catalogues; while using the NEI catalogue all the earthquakes with magnitude greater than 4 are found also with the minimum tested radius (r_0=10 km, see Fig. 11a) the percentage of found earthquakes is smaller using L&G catalogue and increases approximately linearly with radius.

<Figure 10 and 11 here>

Fig. 12 shows the distribution of found earthquakes (white symbols) and of earthquakes for which no seismic quiescence was detected (lost earthquakes – black symbols) setting r_0=10 km (Fig. 12a) and r_0=30 km (Fig. 12b) in the whole time period 1994-2004. Stars represent earthquakes with magnitude $M_L > 5$, dots earthquakes with magnitude $4 < M_L \leq 5$. Fig. 12a shows that, using r_0=10 km, a quiescence is detected for a large percentage of the earthquakes (66% of the earthquakes with magnitude greater than 4, all the earthquakes with magnitude greater than 5) in the central and the southern part of Italian peninsula and Sicily (zone 2 in Fig. 9b); in addition, a quiescence is detected before all earthquakes in Northeastern area of Italy (zone 4 in Fig. 9b; the one analyzed by the NEI catalogue). For the rest of Italy no quiescence is detected before the earthquakes. This is due to the instability of RTL for r_0=10 km in regions where the recorded seismicity is low; the value of RTL_{surv} in these areas could not be evaluated. For zone 3 of Fig. 9b, containing Sardinia and Corsica islands and the most of Tyrrhenian Sea, no reliable value of r_0 can be applied to obtain a stable RTL, due to the very small number of recorded earthquakes (in a rectangle with vertices (N latitude, E longitude)={(42, 9),(42, 11),(40, 11), (40, 9))} around the larger magnitude seismicity in the area , the number of recorded earthquakes from 1994 to 2004 is 14). For most of the northern part of Italy, (zone 1 in the Fig. 9b) it is necessary to use r_0=30 km to obtain the same performance that is obtained in the central-south Italy (zone 2) with r_0=10 km (see Fig. 12b). An analysis by macro-areas is therefore adopted with RTL_{surv} method, neglecting the area 3, where no precursor detection is possible using RTL, until a larger number of earthquakes are recorded in that area.

<Figure 12 here>

Table 7 shows the obtained performances of the method in terms of percentage of area of the seismic quiescence (alarm area) with respect to the whole area of the region analyzed, and in terms of percentage of found earthquakes, depending on the magnitude. The analysis is done by evaluating the RTL_{surv} every 6 months and considering the earthquakes which occurred during the 6 months following the forecast. In order to have a more complete analysis of the method performance, it would be necessary to understand what percentage of the alarm area should be considered a true alarm (the earthquake happens in the alarm area) and what a false alarm. In order to do this, the concept of "false alarm" should be studied in detail. A draft definition of false alarm could be "a false alarm is a detected quiescence region where no earthquake with $M \geq 4$ happens during the six months following the forecast". However, since the extension of the quiescence areas grows with increasing the radius r_0, different quiescence areas merge together, and the number of false alarms defined in the previous way decreases, even if the overall alarm area increases. For this reason, I propose an alternative definition of true and false alarm, analyzing separately all the cells of a grid: "A quiescence cell is considered a true alarm if an earthquake with $M_L \geq 4$ occurs within a distance $2\varepsilon+L/2+2r_0$ during the six months following the forecast; otherwise, it is a false alarm". This definition takes into account the influence of r_0 on RTL and the inaccuracy of location due to the catalogue and the grid discretization. Table 7 lists the percentage of true and false alarms for the zones 1, 2 and 4. From the table, it can be inferred that the percentage of false alarms is high with respect to the whole alarm area. However, if the whole monitored region is considered, the false alarm area is smaller or equal to the 15.5% (see Table 7); considering that and at least 66% of $M \geq 4$ and 100% of $M>5$ earthquakes are found, a good correlation between seismic quiescence and large to medium earthquakes can be deduced.

6. Conclusions

In this paper, the seismicity quiescence before the larger Italian earthquakes from 1994 to the end of 2004 has been analyzed. In particular, the RTL algorithm has been applied. The Chen and Wu (2006) method allows me to obtain r_0 and t_0 parameters for RTL calculated at the epicenter of large earthquakes. Using these parameters on 12 M>5 earthquakes which occurred in Italy in the time period from January 1994 to December 2004, a quiescence phase is detected in 92% of the cases, while only 25% of the earthquakes are preceded by an activation phase. The duration of the quiescence and the time shift from the end of the quiescence to the earthquake time have been evaluated and ranges from 0.6 to 3 years and 0 to 2.9 years respectively, with a time interval from the start of the quiescence to the main shock ranging from 0.6 to 4 years. The obtained parameters have been applied also to the mapping of the quiescence region before the earthquake. The quiescence regions appear in some cases very large, due to the high value of r_0. For this reason, a simple method for the best choice of the parameters is proposed and tested on the M>5 earthquakes. The results are improved for 10 of the 11 cases in which the earthquake was preceded by a quiescence, and remain unchanged in the other. The quiescence regions detected by this method are characterized by linear dimensions ranging 50 to 450 km with mean value 164 km.

A survey method based on RTL for the whole Italy analysis is proposed. The aim of the method, named RTL_{surv}, is to make a survey of the Italian area, in order to detect seismic quiescence zones that may give rise to large earthquakes. The advantage of the method is that it is not necessary to define a-priori the analysis time window. RTL_{surv} has been tested on declustered catalogues for the earthquakes with $M_L \geq 4$ in the time interval 1st January 1994-31st December 2004. The Italian area was divided into 4 zones with different characteristics of the recorded seismicity. One of the zones (North and Central Tyrrhenian sea) is characterized by too low a number of recorded earthquakes for the analysis. For each of the other three zones a parameter r_0 was found for which at least the 66% of the earthquakes with $M_L>4$ and all the earthquakes with $M_L>5$ were

preceded by a detected seismic quiescence. The overall alarm area ranges from 8.7% to 18.4% of the whole analyzed region area, depending on the zone analyzed and on parameter r_0.

Even if the results found in this paper are encouraging, I wish to emphasize which are the limits of the method:

1. The time shift between the detection of a quiescence and the earthquake can be long and therefore it has been necessary to select a long time analysis for the RTL_{surv} (4 years). This fact, together with the impossibility of discriminating between an isolated M≥4 mainshock and a swarm of M≥4 earthquakes during even tens of months, means that after a M≥4 earthquake the surrounding region may remain an alarm area for a long time, even if no earthquake follows, generating false alarms.
2. The area covered by the quiescence zone can be large, especially in regions characterized by a low recorded seismicity, not allowing us to have indications for a reasonable economic planning of constructions, timely preparation of a potential future damage and correct land use.

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Figure Captions

Figure 1: Cumulative number of earthquakes with M_D>0 in (a) the NEI catalogue and (b) the L&G catalogue. Vertical dashed lines: the time window of data recording interruption for the NEI catalogue; black continuous line: catalogue before the declustering; black arrows: increases of seismicity; grey continuous line: catalogue after the modified Knopoff algorithm declustering; black dashed line: catalogue after the Reasenberg declustering using default parameters; grey dashed line: catalogue after the Reasenberg declustering using Lolli and Gasperini parameters.

Figure 2: Seismic moment M_0 as a function of duration magnitude M_D in NE Italy area. Data from Franceschina et al 2006 and Bressan et al. 2007.

Figure 3: Changes with time of the magnitude of completeness for (a) NEI catalogue (duration magnitude) (b) Lolli and Gasperini catalogue (local magnitude).

Figure 4: RTL calculated at the epicenters of analyzed earthquakes using the parameters listed in Table 3 (thick line) and standard parameters r_0=30 km t_0=1 year (thin grey line) until the midnight before the mainshock. Adopted declustering method: modified Knopoff algorithm. Epicenter location: (a) Gargano (Apulia) (b) Reggio Emilia (c) Umbria Marche (d) Kobarid (1998) (e) Calabrian-Lucanian Apennines (f) Merano (g) Sernio Mountain (h) Palermo (i) Molise (l) Adriatic Sea (m) Kobarid (2004) (n) Garda Lake.

Figure 5: RTL calculated at the epicenters of NE Italy earthquakes using L&G catalogue and the parameters r_0 and t_0 calculated by Chen and Wu method on the same catalogue. Epicenter location: (a) Kobarid (1998) r_0=35 km t_0=1.8 years (b) Sernio Mountain r_0=55 km t_0=0.4 years (c) Kobarid (2004) r_0=30 km t_0=1.3 years.

Figure 6: RTL calculated at the epicenters of analyzed earthquakes using the parameters listed in Table 3 (thick line) and standard parameters r_0=30 km t_0=1 year (thin grey line) until the midnight before the mainshock. Adopted declustering method: Reasenberg declustering algorithm with Lolli and Gasperini parameters. Epicenter location: (a) Gargano (Apulia) (b) Reggio Emilia (c)

Umbria Marche (d) Kobarid (1998) (e) Calabrian-Lucanian Apennines (f) Merano (g) Sernio Mountain (h) Palermo (i) Molise (l) Adriatic Sea (m) Kobarid (2004) (n) Garda Lake.

Figure 7: Map of the RTL using the Q method (grayscale), t_0 obtained by Cheng and Wu method and r_0 using minimum radius method (see Table 6)). The white star represents the epicenter location for: (a) Gargano (Apulia) (b) Reggio Emilia (c) Umbria Marche (d) Kobarid (1998) (e) Calabrian-Lucanian Apennines (f) Merano (g) Sernio Mountain (h) Palermo (i) Molise (l) Adriatic Sea (m) Kobarid (2004) (n) Garda Lake.

Figure 8: Map of the RTL using the Q method, at the epicenter of Umbria Marche earthquake using t_0=0.6 years and (a) r_0=35 km (b) r_0=30 km.

Figure 9: Map of Italy with (a) regions analyzed by L&G and NEI catalogues (b) Draft subdivision into macro-areas as a function of the number of recorded earthquakes.

Figure 10: Behaviour of r_0 for the L&G catalogue (see Fig. 9a): (a) Percentage of earthquakes with $M_L \geq 4$ for which a precursory quiescence is detected as function of parameter r_0 adopted (b) percentage of the area characterized by a detected seismic quiescence as function of parameter r_0 adopted.

Figure 11: Behaviour of r_0 for the NEI catalogue (see Fig. 9a): (a) Percentage of earthquakes with $M_D \geq 3.9$ (corresponding approximately with $M_L \geq 4$) for which a precursory quiescence is detected as function of parameter r_0 adopted (b) percentage of the area characterized by a detected seismic quiescence as function of parameter r_0 adopted.

Figure 12: Map of the earthquakes preceded by a detected quiescence (white symbols) and not (black symbols). Stars correspond to earthquakes with $M_L > 5$, circles to earthquakes with $4 \leq M_L \leq 5$. (a) r_0=10 km (b) r_0=30 km.

Table captions

Table 1: All the earthquakes with M_L>5 listed in L&G and NEI catalogues. The earthquakes outlined in boldface are the ones analyzed in this paper. Lat and Lon: north latitude and east longitude of the main shock (degrees); M_L (L&G): local magnitude as listed in L&G catalogue; M_D (NEI): duration magnitude as listed in NEI catalogue.

Table 2: Analyzed earthquakes and adopted completeness magnitude. Catalogue: catalogue adopted for the analysis; Magnitude: type of magnitude listed; M_c: completeness magnitude inside a circle of radius 100 km centered at the epicenter in the magnitude units of the adopted catalogue.

Table 3: The t_0 and r_0 values selected by Chen and Wu (2006) method and the corresponding peak values $p(t_0)$ and $p(r_0)$.

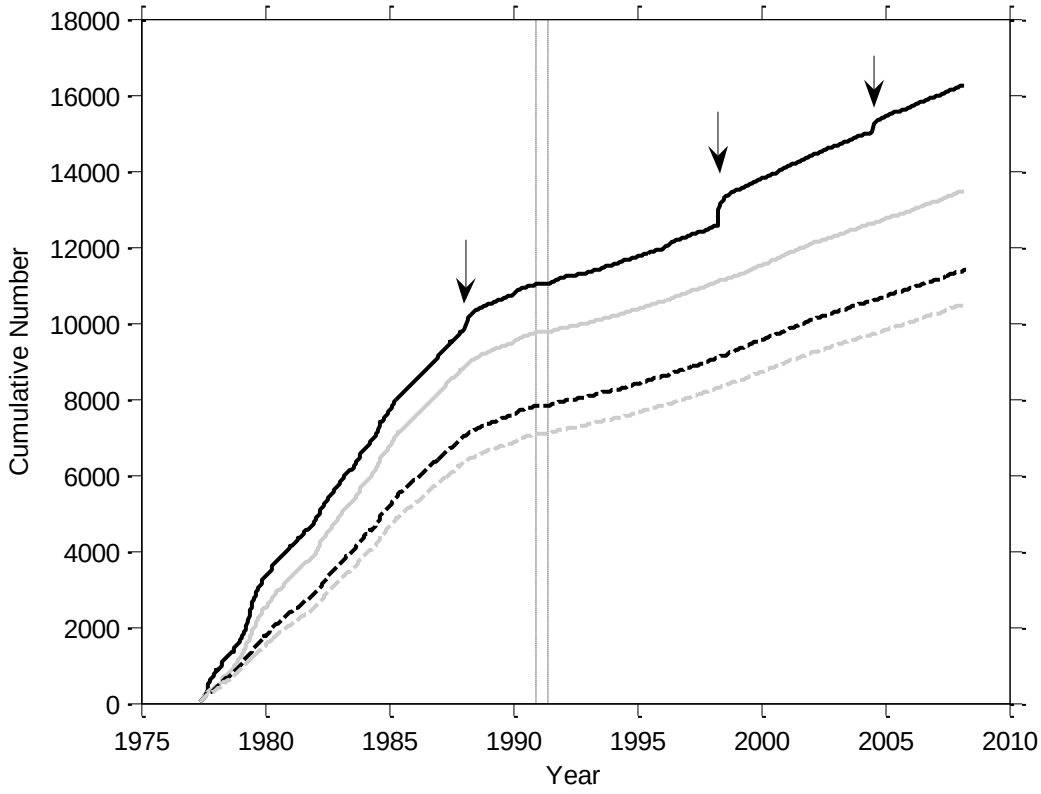
Table 4: Minimum (M_{min}) and maximum (M_{max}) magnitude threshold used for calculation for which the quiescence before the analyzed earthquakes is detected. Adopted magnitude threshold (completeness magnitude M_c) is shown for comparison.

Table 5: The characteristics of quiescences and activation phases detected by the RTL obtained at the epicenter of the analyzed earthquakes, using the parameters listed in Table 3.

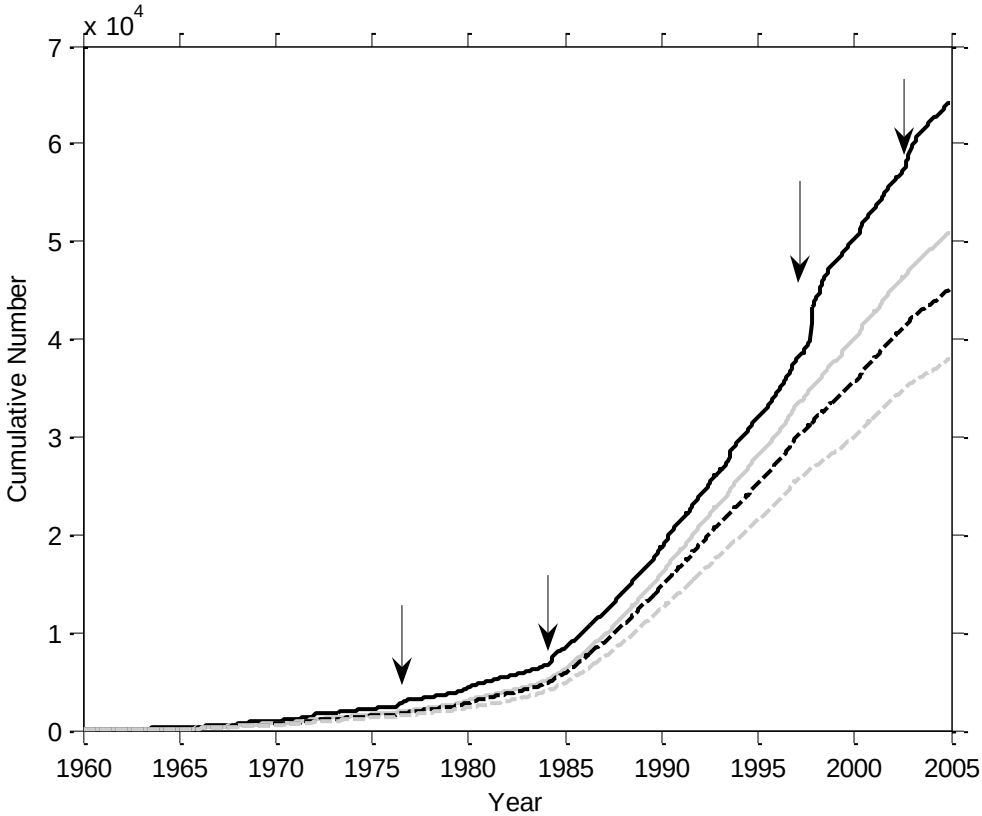
Table 6: Adopted parameters in RTL map construction by applying (i) Cheng and Wu method (ii) Threshold on r_0 (iii) Minimum radius. For each choice, the corresponding quiescence anomaly linear dimension is listed.

Table 7: Performances of the RTL_{surv} method on three zones shown in Fig. 9b.

Figures

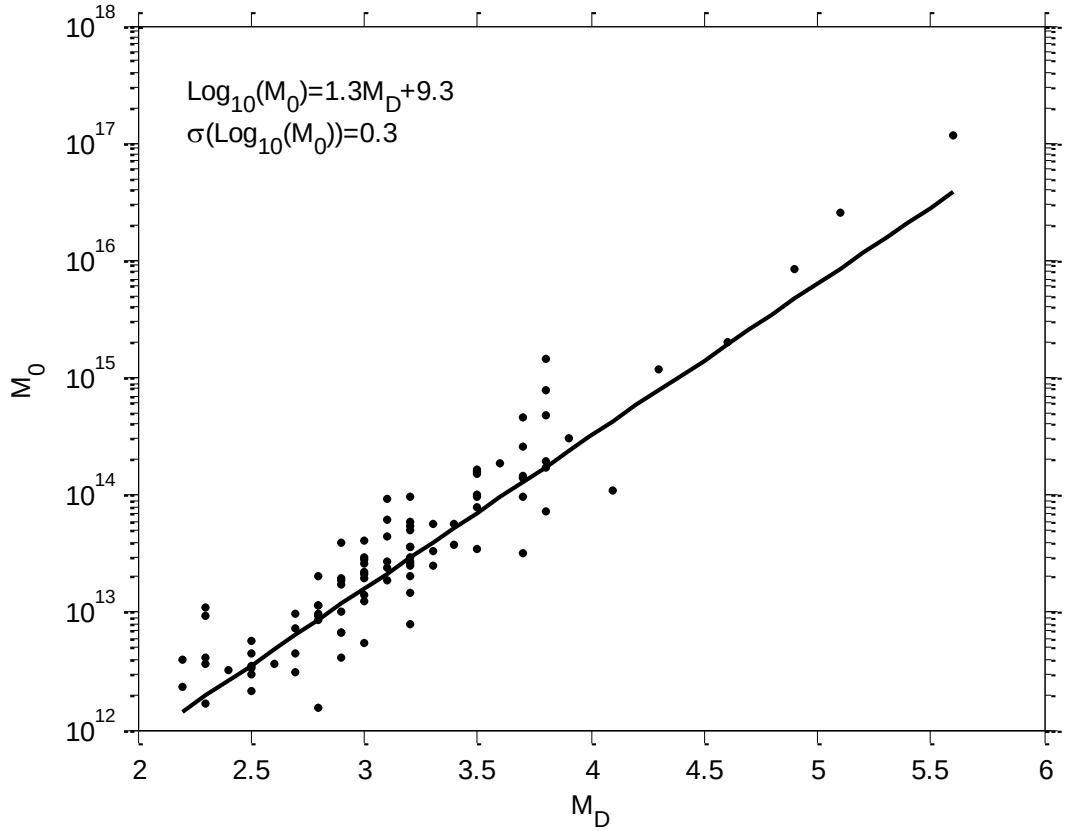

18000
16000
14000
12000
10000
8000
6000
4000
2000
0
Cumulative Number
1975
1980
1985
1990
1995
2000
2005
2010
Year

(a)


x 10^4
7
6
5
4
3
2
1
0
Cumulative Number
1960
1965
1970
1975
1980
1985
1990
1995
2000
2005
Year

(b)

Figure 1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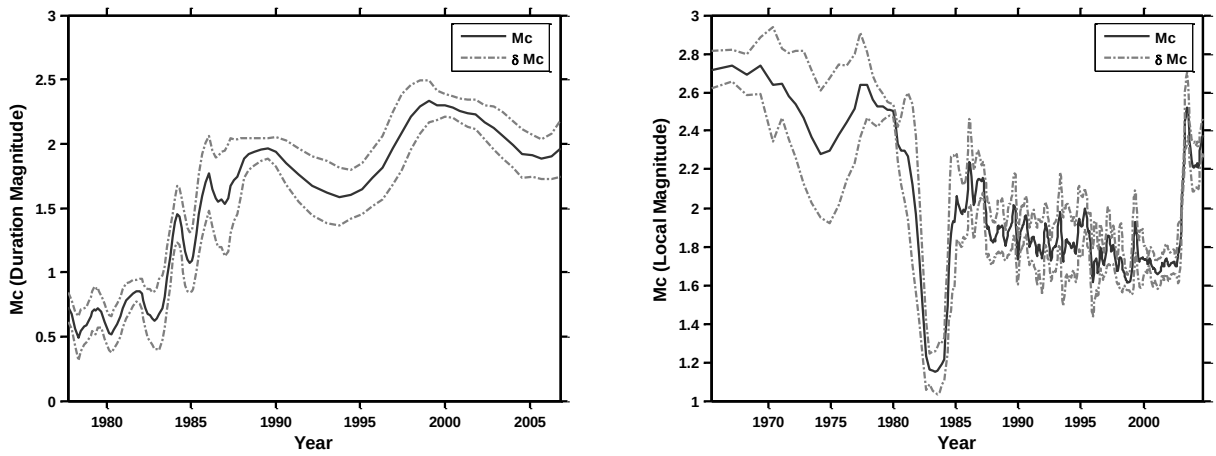
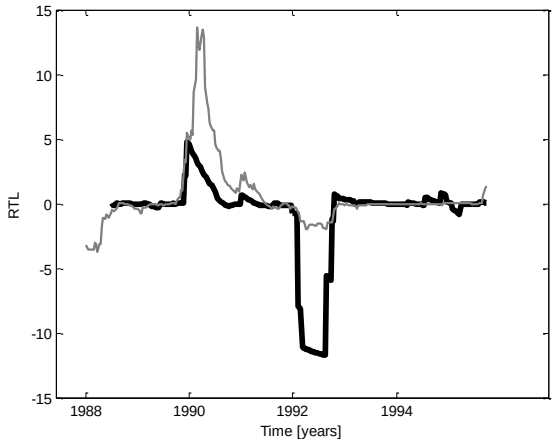
σ(Log10(M0))=0.3
10^18
10^17
10^16
10^15
10^14
10^13
10^12
M0
2
2.5
3
3.5
4
4.5
5
5.5
6
MD

Figure 2

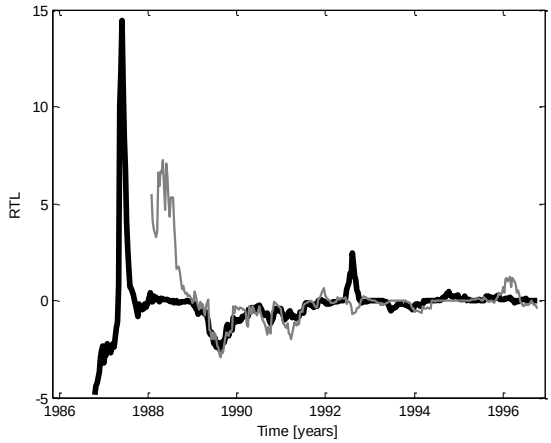

Mc
δ Mc
Mc (Duration Magnitude)
Year
Mc
δ Mc
Mc (Local Magnitude)
Year

(a) (b)

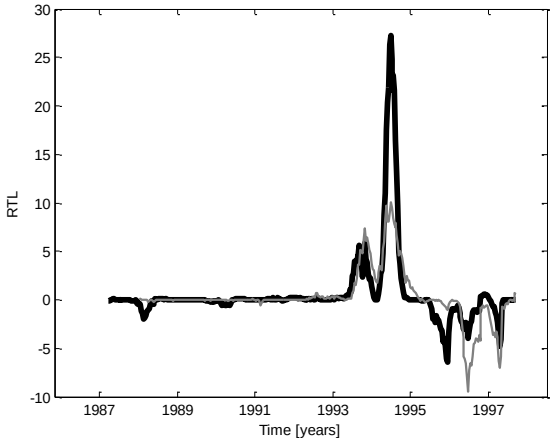
Figure 3


RTL
Time [years]

(a)


RTL
Time [years]

(b)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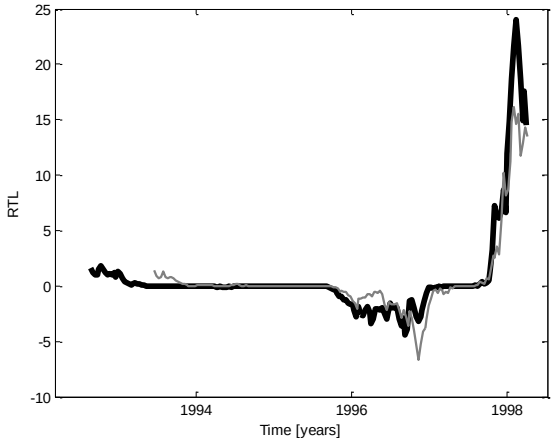
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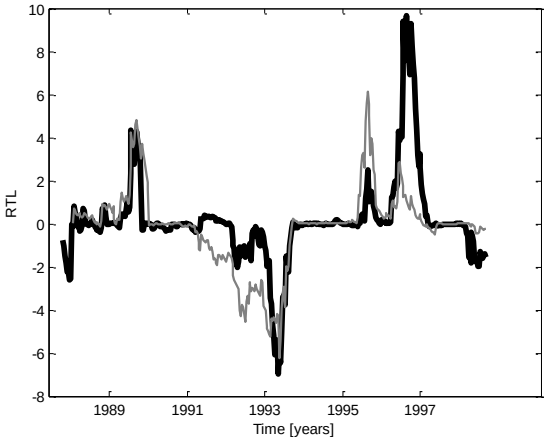
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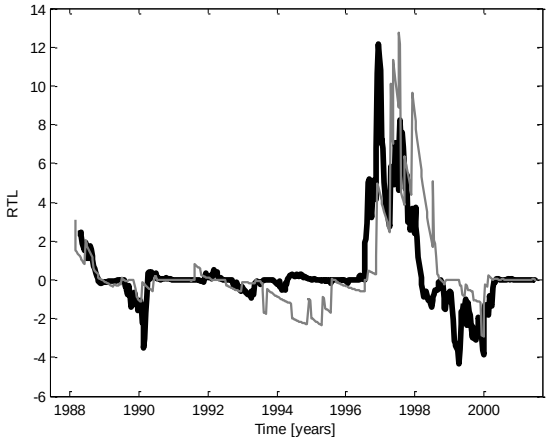
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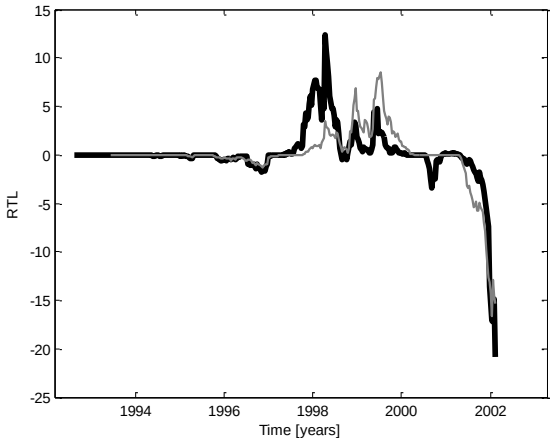

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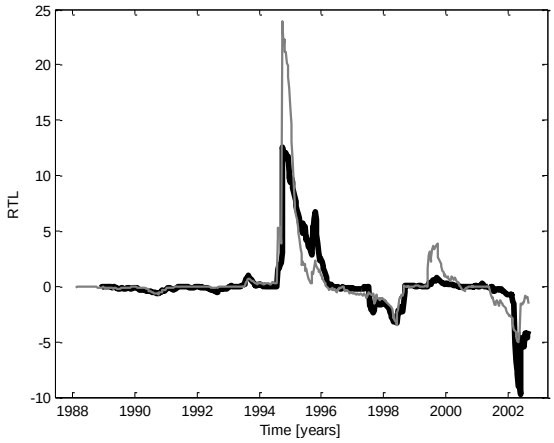

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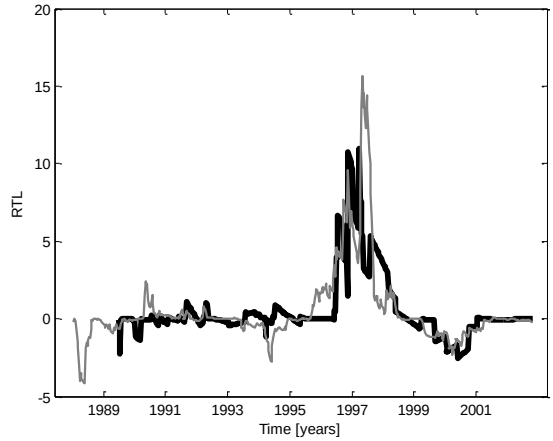

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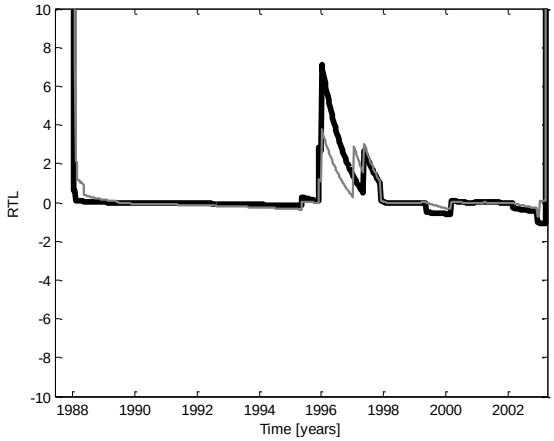

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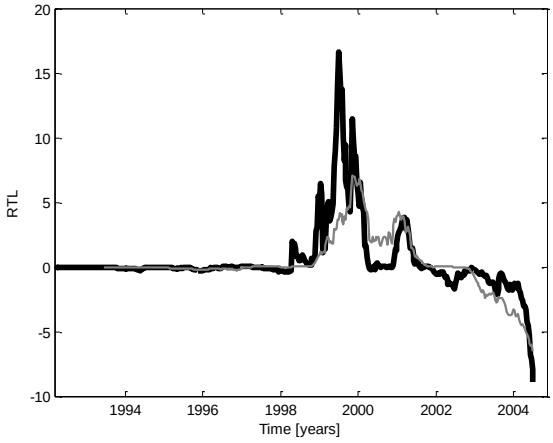

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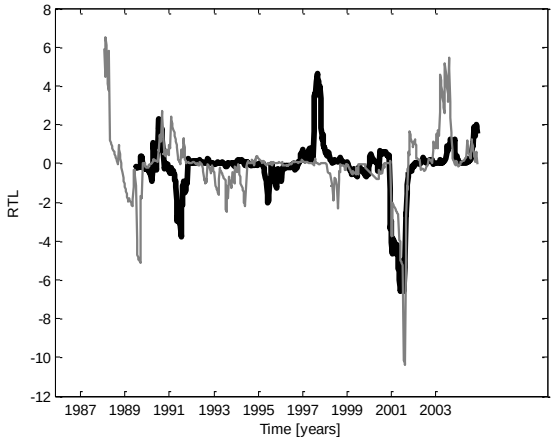

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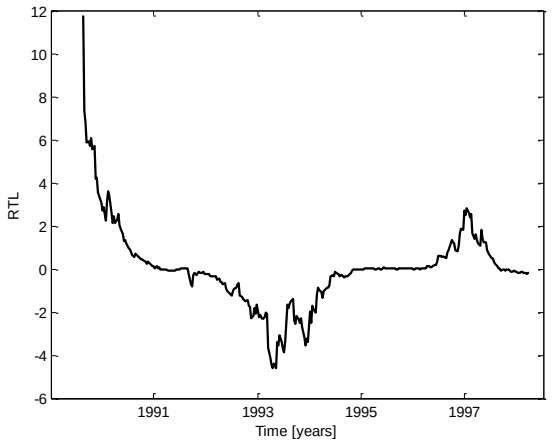

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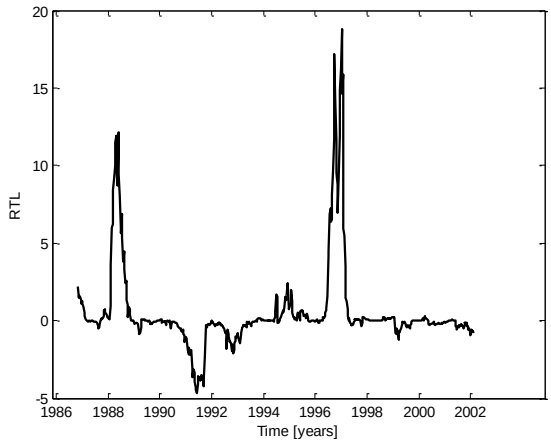

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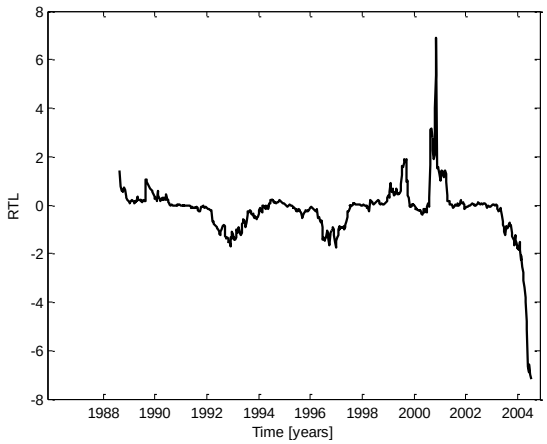

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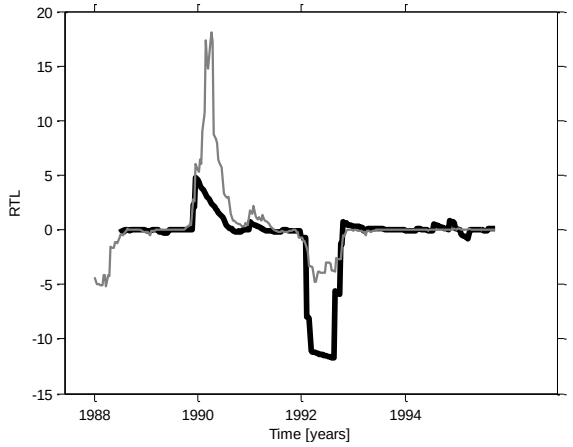
RTL
Time [years]

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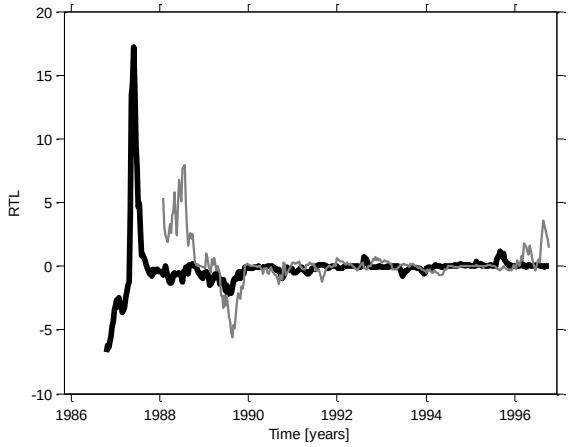
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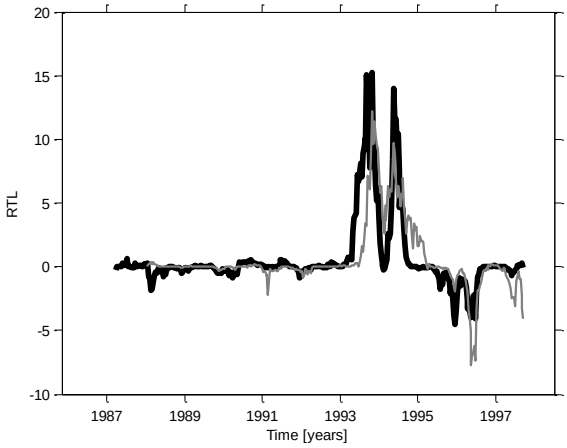
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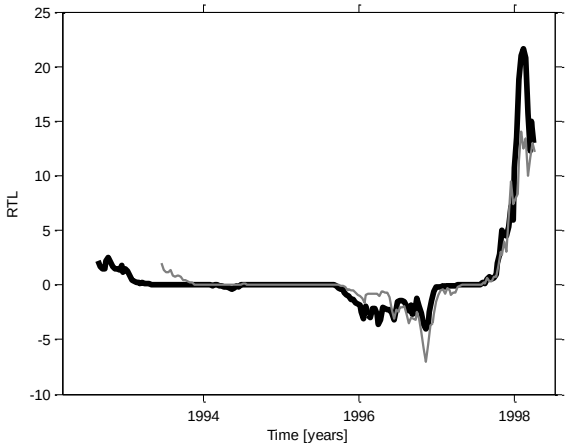
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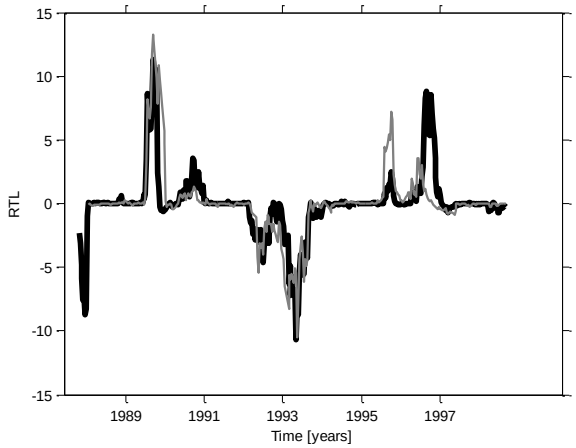
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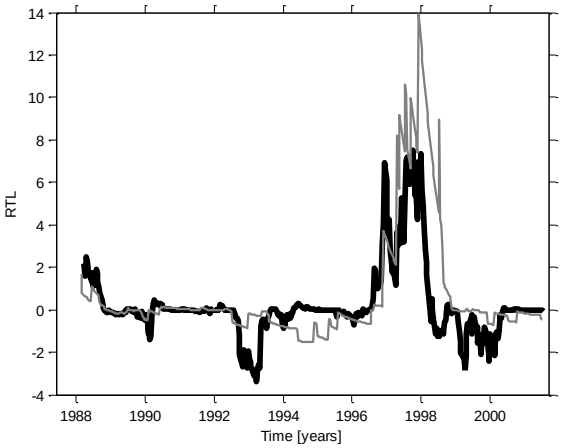
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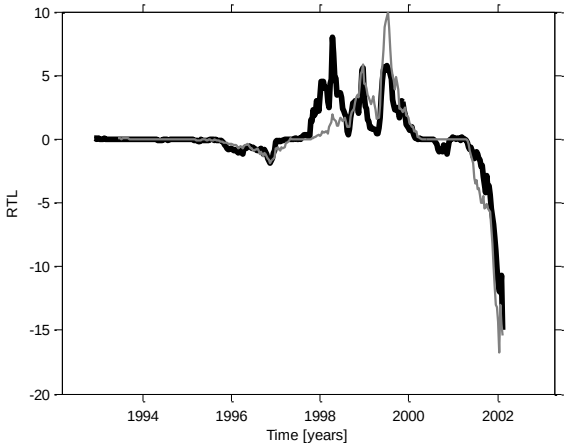

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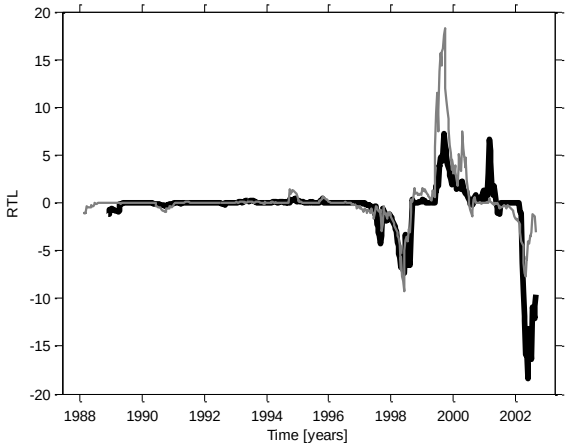

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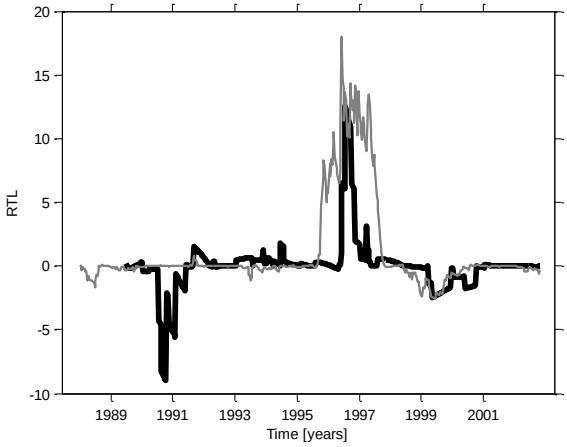

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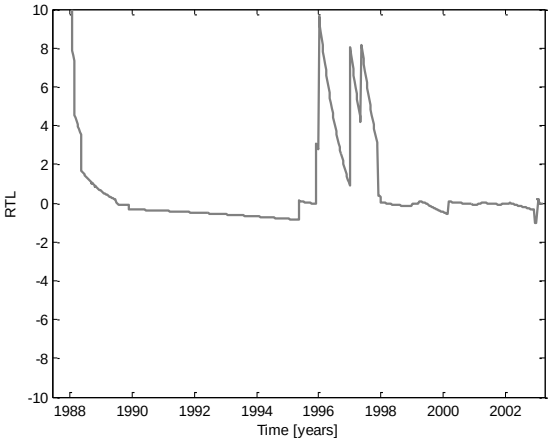

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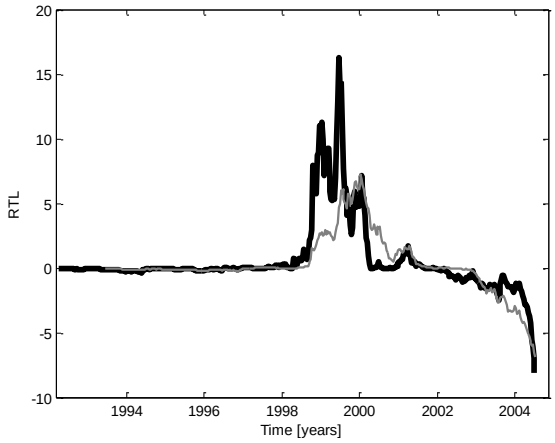

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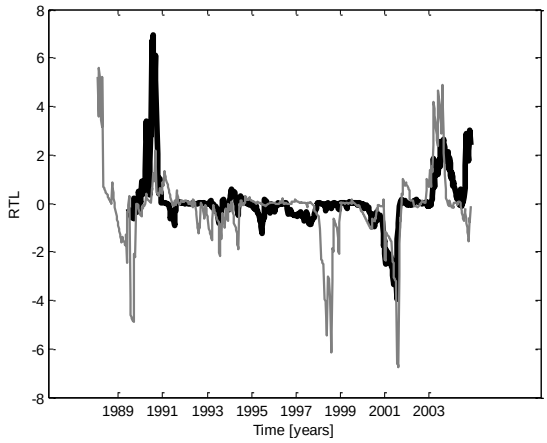

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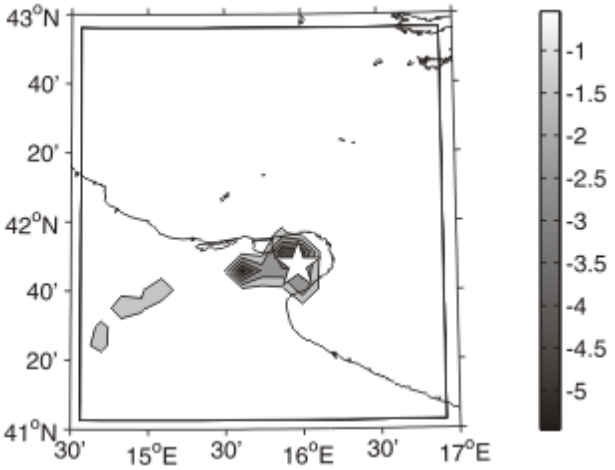
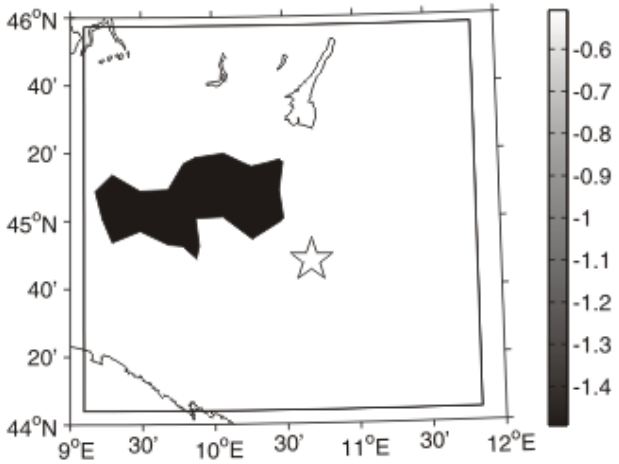
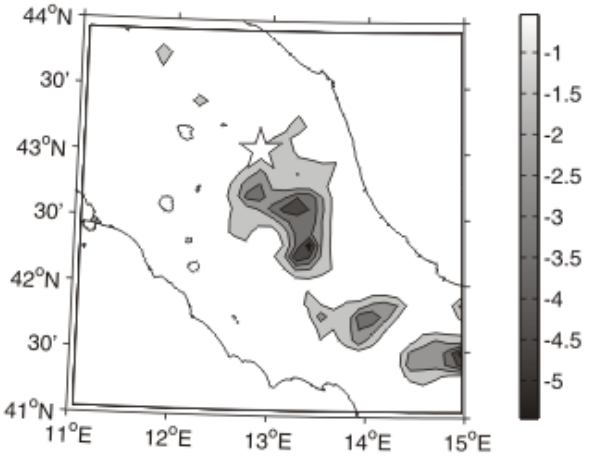

43°N
40'
20'
42°N
40'
20'
41°N
30'
15°E
30'
16°E
30'
17°E
-1
-1.5
-2
-2.5
-3
-3.5
-4
-4.5
-5

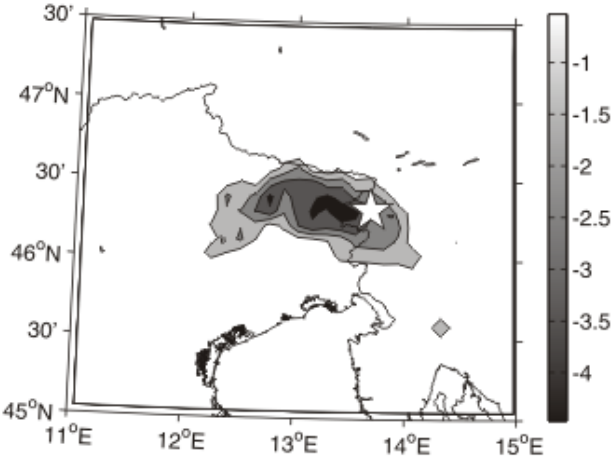
(a)


46°N
40'
20'
45°N
40'
20'
44°N
9°E
30'
10°E
30'
11°E
30'
12°E
-0.6
-0.7
-0.8
-0.9
-1
-1.1
-1.2
-1.3
-1.4

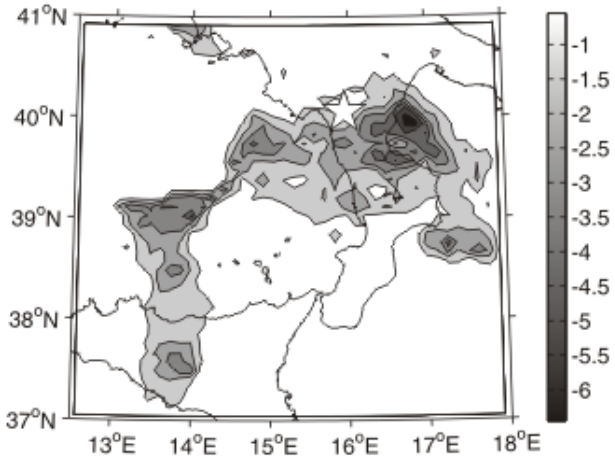
(b)


44°N
30'
43°N
30'
42°N
30'
41°N
11°E
12°E
13°E
14°E
15°E
-1
-1.5
-2
-2.5
-3
-3.5
-4
-4.5
-5

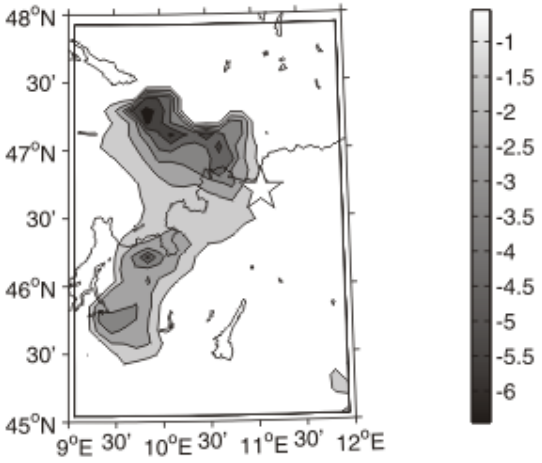
(c)


30'
47°N
30'
46°N
30'
45°N
11°E
12°E
13°E
14°E
15°E
-1
-1.5
-2
-2.5
-3
-3.5
-4

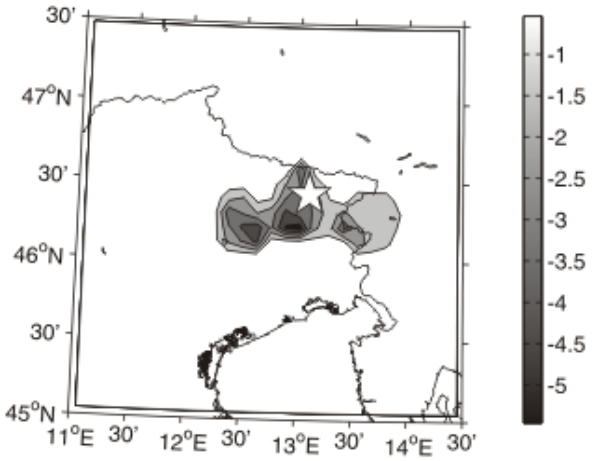
(d)


41°N
40°N
39°N
38°N
37°N
13°E
14°E
15°E
16°E
17°E
18°E
-1
-1.5
-2
-2.5
-3
-3.5
-4
-4.5
-5
-5.5
-6

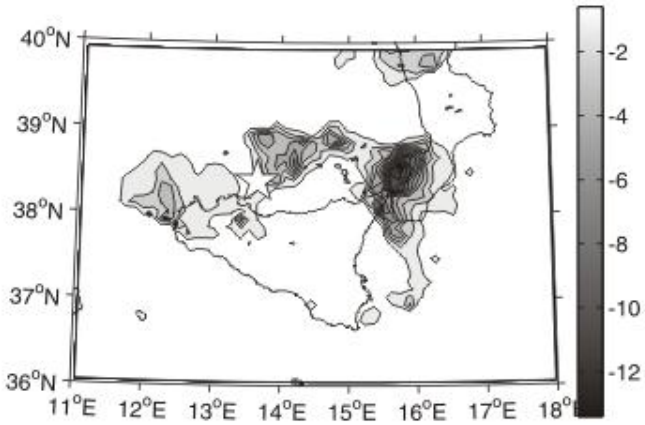
(e)


48°N
30'
47°N
30'
46°N
30'
45°N
9°E
30'
10°E
30'
11°E
30'
12°E
-1
-1.5
-2
-2.5
-3
-3.5
-4
-4.5
-5
-5.5
-6

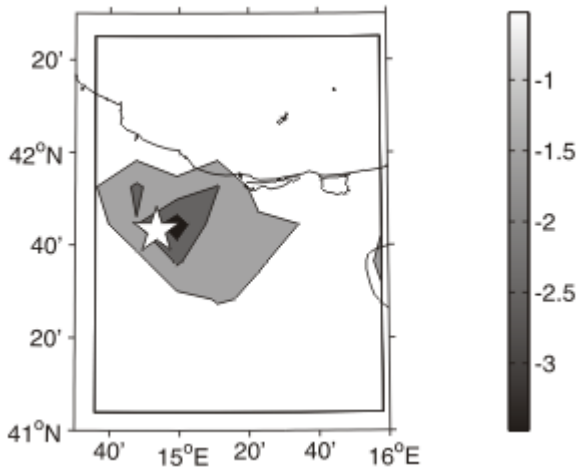
(f)



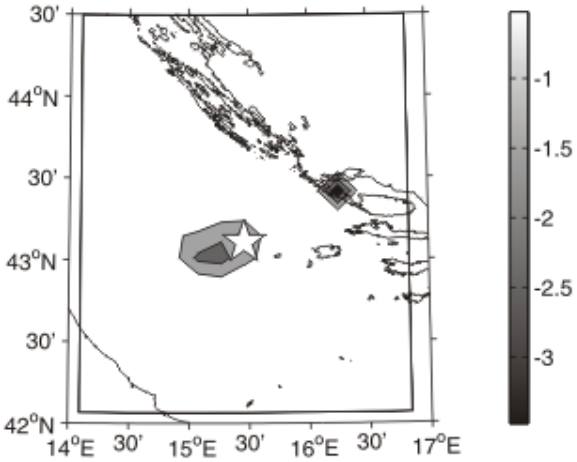
(g)



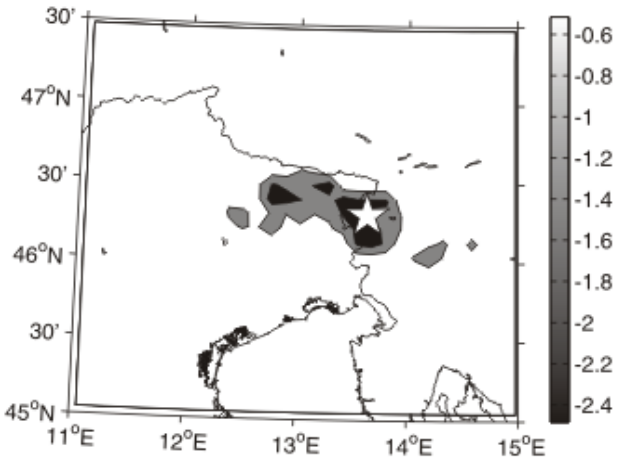
(h)



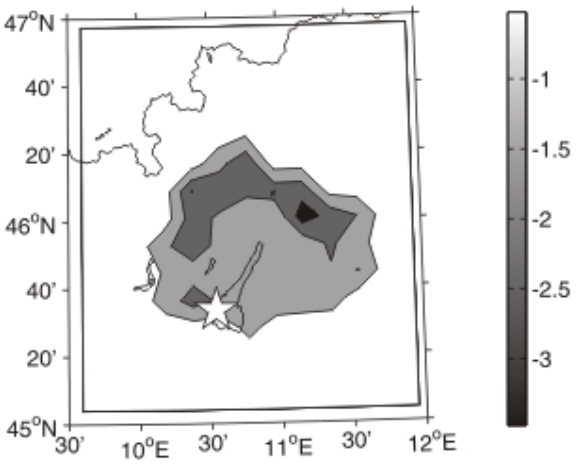
(i)



(l)

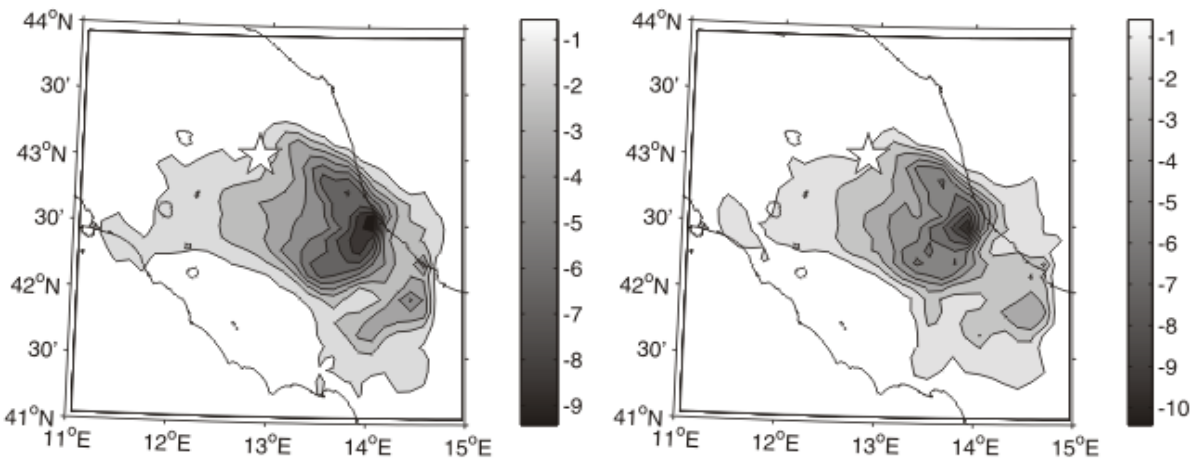


(m)



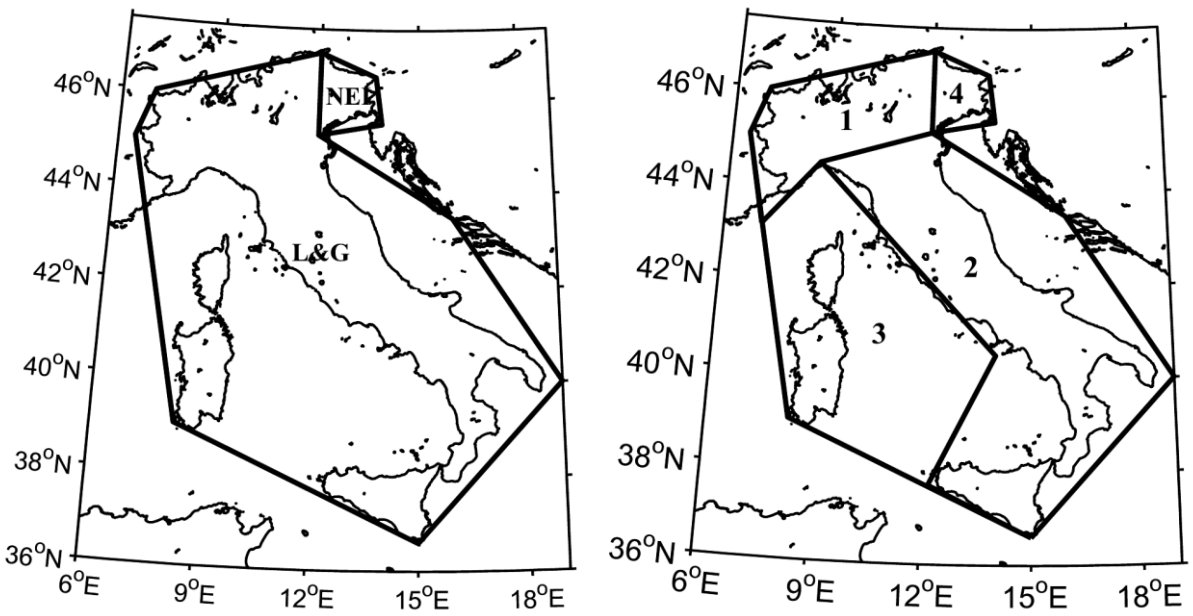
(n)

Figure 7


44°N
30'
43°N
30'
42°N
30'
41°N
11°E
12°E
13°E
14°E
15°E
-1
-2
-3
-4
-5
-6
-7
-8
-9
44°N
30'
43°N
30'
42°N
30'
41°N
11°E
12°E
13°E
14°E
15°E
-1
-2
-3
-4
-5
-6
-7
-8
-9
-10

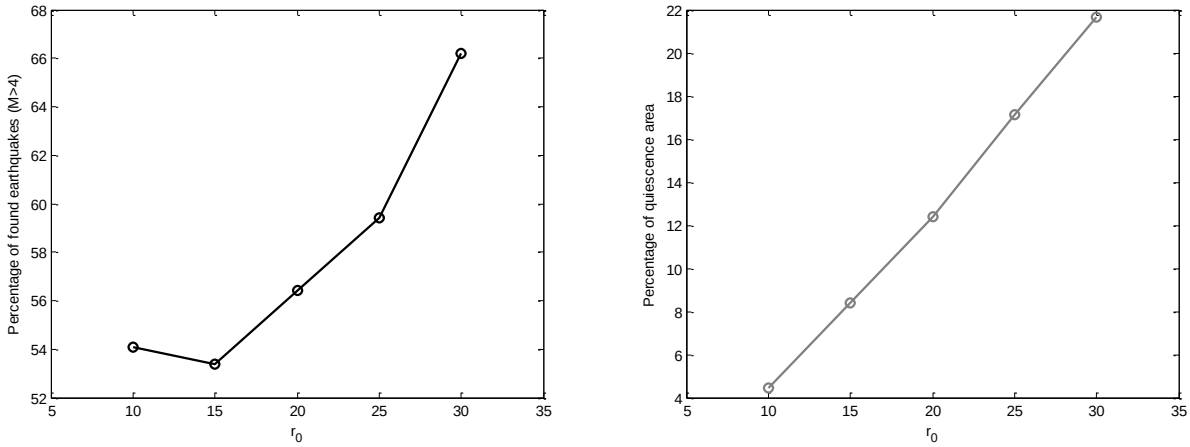
(a) (b)

Figure 8



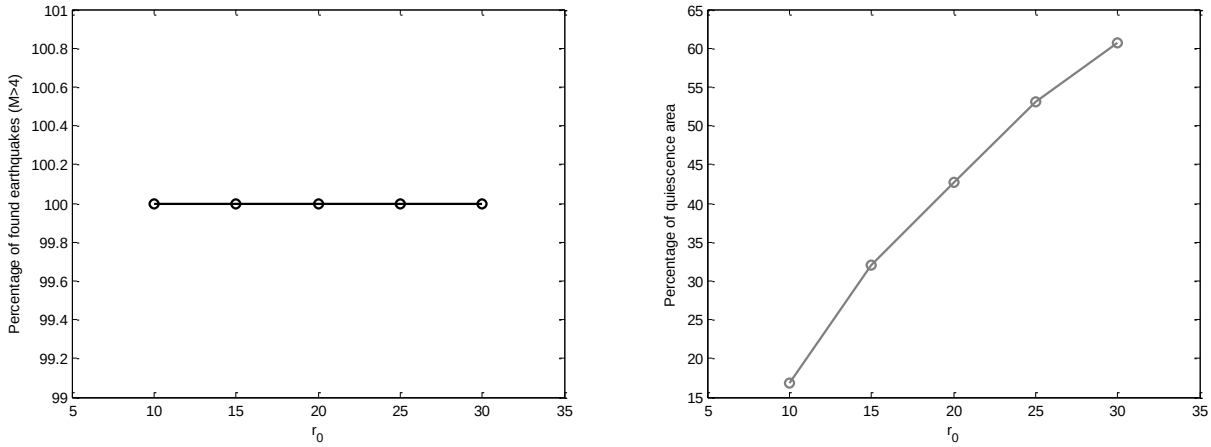
(a) (b)

Figure 9


Percentage of found earthquakes (M>4)
68
66
64
62
60
58
56
54
52
5
10
15
20
25
30
35
r0
Percentage of quiescence area
22
20
18
16
14
12
10
8
6
4
5
10
15
20
25
30
35
r0

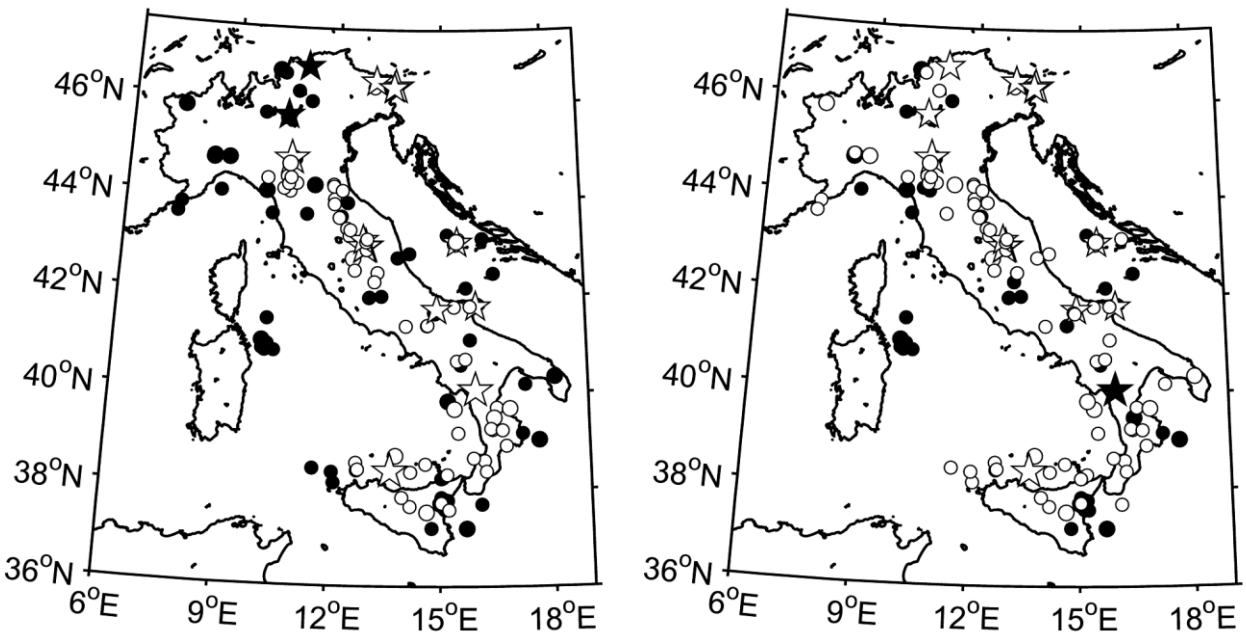
(a) (b)

Figure 10


Percentage of found earthquakes (M>4)
101
100.8
100.6
100.4
100.2
100
99.8
99.6
99.4
99.2
99
5
10
15
20
25
30
35
r0
Percentage of quiescence area
65
60
55
50
45
40
35
30
25
20
15
5
10
15
20
25
30
35
r0

(a) (b)

Figure 11


46°N
44°N
42°N
40°N
38°N
36°N
6°E
9°E
12°E
15°E
18°E
46°N
44°N
42°N
40°N
38°N
36°N
6°E
9°E
12°E
15°E
18°E

(a) (b)

Figure 12

Tables

Date (UTC)	Time (UTC)	Zone	Lat [deg]	Lon [deg]	Depth [km]	M_L (L&G)	M_D (NEI)
1994/01/05	*13:24:08*	*South Tyrrhenian Sea*	*38.97*	*15.41*	*307*	*5.7*	-
1995/09/30	**10:14:34**	**Gargano (Apulia)**	**41.79**	**15.97**	**28**	**5.4**	-
1996/10/15	**09:56:00**	**Reggio Emilia**	**44.80**	**10.68**	**1**	**5.5**	-
1997/09/26	**00:33:13**	**Umbria Marche**	**43.02**	**12.89**	**4**	**5.6**	-
1997/09/26	*09:40:27*	*Umbria Marche*	*43.01*	*12.85*	*10*	*5.8*	-
1997/10/06	*23:24:53*	*Umbria Marche*	*43.03*	*12.85*	*4*	*5.4*	-
1997/10/12	*11:08:37*	*Umbria Marche*	*42.91*	*12.92*	*0*	*5.1*	-
1997/10/14	*15:23:11*	*Umbria Marche*	*42.90*	*12.90*	*7*	*5.5*	-
1998/03/26	*16:26:17*	*Umbria Marche*	*43.15*	*12.81*	*45*	*5.4*	-
1998/04/03	*07:26:37*	*Umbria Marche*	*43.19*	*12.76*	*2*	*5.3*	-
1998/04/12	**10:55:33**	**Kobarid**	**46.32**	**13.68**	**15**	**5.6**	**5.6**
1998/05/18	*17:19:11*	*South Tyrrhenian Sea*	*39.06*	*15.02*	*219*	*5.4*	-
1998/09/09	**11:28:00**	**Calabrian-Lucanian Apennines**	**40.06**	**15.95**	**29**	**5.6**	-
2001/07/17	**15:06:15**	**Merano**	**46.70**	**11.07**	**0**	**5.3**	**5.2**
2002/02/14	**03:18:03**	**Sernio Mountain**	**46.43**	**13.10**	**11**	**4.9**	**4.9**
2002/09/06	**01:21:29**	**Palermo**	**38.38**	**13.65**	**27**	**5.6**	-
2002/10/31	**10:32:59**	**Molise**	**41.72**	**14.89**	**25**	**5.4**	-
2002/11/01	*15:09:02*	*Molise*	*41.74*	*14.84*	*21*	*5.3*	-
2003/03/29	**17:42:16**	**Adriatic Sea**	**43.11**	**15.46**	**10**	**5.4**	-
2004/05/05	*13:39:43*	*Aeolian Islands*	*38.51*	*14.88*	*240*	*5.3*	-
2004/07/12	**13:04:07**	**Kobarid**	**46.30**	**13.63**	**5**	**5.2**	**5.1**
2004/11/24	**22:59:39**	**Garda Lake**	**45.56**	**10.57**	**5**	**5.2**	**4.9**

Table 1

Date	Zone	Catalogue	Magnitude	M_c
1995/09/30	Gargano (Apulia)	L&G	M_L	2.5
1996/10/15	Reggio Emilia	L&G	M_L	2.0
1997/09/26	Umbria Marche	L&G	M_L	2.0
1998/04/12	Kobarid	NEI	M_D	2.2
1998/09/09	Calabrian-Lucanian Apennines	L&G	M_L	2.2
2001/07/17	Merano	L&G	M_L	2.1
2002/02/14	Sernio Mountain	NEI	M_D	2.4
2002/09/06	Palermo	L&G	M_L	2.3
2002/10/31	Molise	L&G	M_L	2.3
2003/03/29	Adriatic Sea	L&G	M_L	2.7
2004/07/12	Kobarid	NEI	M_D	2.3
2004/11/24	Garda Lake	L&G	M_L	2.2

Table 2

Zone	t_0 [years]	$p(t_0)$	r_0 [km]	$p(r_0)$
Gargano (Apulia)	1.1	47%	15	76%
Reggio Emilia	0.4	92%	55	43%
Umbria Marche	0.6	93%	35	100%
Kobarid 1998	0.6	100%	60	98%
Calabrian-Lucanian Apennines	0.9	55%	45	93%
Merano	1.1	53%	65	92%
Sernio Mountain	0.6	100%	25	100%
Palermo	1.4	45%	30	99%
Molise	1.4	77%	15	86%
Adriatic Sea	1.0	72%	25	52%
Kobarid 2004	0.4	100%	40	92%
Garda Lake	1.7	22%	55	67%

Table 3

Zone	M_c	M_{min}	M_{max}
Gargano (Apulia)	2.5	0	2.8
Reggio Emilia	2.0	-	-
Umbria Marche	2.0	0	3.5
Kobarid	2.2	0	3.3
Calabrian-Lucanian Apennines	2.2	0	3.5
Merano	2.1	1.5	3.1
Sernio Mountain	2.4	0	3.1
Palermo	2.3	0	3.1
Molise	2.3	0	2.8
Adriatic Sea	2.7	0	3.1
Kobarid	2.3	0	3.2
Garda Lake	2.2	0	3.2

Table 4

Zone	Quiescence Duration [years]	Quiescence shift [years]	Activation Duration [years]	Activation Shift [years]
Gargano (Apulia)	1.1	2.9	-	-
Reggio Emilia	-	-	-	-
Umbria Marche	2.0	0.3	-	-
Kobarid 1998	1.6	1.0	0.7	0
Calabrian-Lucanian Apennines	0.6	0	-	-
Merano	2.2	1.2	-	-
Sernio Mountain	0.6	0	-	-
Palermo	1.4	0	-	-
Molise	1.4	1.8	-	-
Adriatic Sea	1.5	0.03	0.03	0
Kobarid 2004	3.0	0	-	-
Garda Lake	1.2	2.8	0.5	0

Table 5

Zone	M_c	Analysis time interval [year/month/day]	Cheng and Wu		Threshold on r_0		Minimum radius	
			r_0 [km]	Quiescence anomaly dimension	r_0 [km]	Quiescence anomaly dimension	r_0 [km]	Quiescence anomaly dimension
Gargano (Apulia)	2.5	1991/10/25-1992/10/26	15	~100 km	15	~100 km	10	~50 km
Reggio Emilia	2.1	1995/10/16-1996/10/15	55	-	30	-	-	-
Umbria Marche	2.2	1995/07/02-1996/07/01	35	~300 km	30	~300 km	10	~150 km
Kobarid 1998	2.2	1995/12/01-1996/11/30	60	~350 km	30	~250 km	10	~150 km
Calabrian-Lucanian Apennines	2.4	1997/09/10-1998/09/09	45	~500 km	30	~450 km	30	~450 km
Merano	2.1	1999/01/28-2000/01/27	65	~800 km	30	~200 km	30	~200 km
Sernio Mountain	2.4	2001/02/14-2002/02/13	25	~200 km	25	~200 km	10	~150 km
Palermo	2.3	2001/09/06-2002/09/05	30	~500 km	30	~500 km	10	~100 km
Molise	2.3	1999/10/29-2000/10/28	15	~100 km	15	~100 km	15	~100 km
Adriatic Sea	2.7	2002/03/17-2003/03/16	25	~150 km	25	~150 km	20	~50 km
Kobarid 2004	2.4	2003/07/12-2004/07/11	40	~350 km	30	~300 km	10	~100 km
Garda Lake	2.2	2000/12/28-2001/12/27	55	~600 km	30	~300 km	30	~300 km

Table 6

Zone number	r_0 [km]	Alarm area	True alarm	False alarm	Found earth. M_L>4	Found earth. M_L>5
1	30	18.4 %	2.9 %	15.5 %	66.7%	100%
2	10	8.7 %	1.2 %	7.5 %	66.0%	100%
4	10	16.9 %	1.9 %	14.9 %	100.0%	100%

Table 7