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Time-clustering analysis of the 1978–2008 sub-crustal seismicity of Vrancea region

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Abstract. The analysis of time-clustering behaviour of the sub-crustal seismicity (depth larger than 60 km) of the Vrancea region has been performed. The time span of the analyzed catalogue is from 1978 to 2008, and only the events with a magnitude of $M_w \geq 3$ have been considered. The analysis, carried out on the full and aftershock-depleted catalogues, was performed using the Allan Factor (AF) that allows the identificatiion and quantification of correlated temporal structures in temporal point processes. Our results, whose significance was analysed by means of two methods of generation of surrogate series, reveal the presence of time-clustering behaviour in the temporal distribution of seismicity data of the full catalogue. The analysis performed on the aftershock-depleted catalogue indicates that the time-clustering is associated mainly to the aftershocks generated by the two largest events occurred on 30 August 1986 ($M_w = 7.1$) and 30 May 1990 ($M_w = 6.9$).

1 Introduction

Among the several aims to which seismological studies are devoted, the time dynamical characterization of seismic sequences is one of the main goals. In fact, within the general context of seismic hazard analysis, the capability of reliably estimating the probability of future earthquake occurrences is based on the knowledge of the statistical distribution of event occurrence. Even if among the several statistical distributions used to model the time seismic occurrences, probably the first and most extensively used was the Poissonian distribution (exponential decreasing function of the interevent times) due to its effectiveness in fittting large events. Some characteristics of Poissonian processes (absence of memory phenomena, independence and uncorrelation of all the events) do not feature most seismic sequences. In fact, Kagan and Jackson (1991) showed that earthquakes present correlation properties at both short and long time scales. This property, called time-clusterization, was widely observed in several seismic catalogues (Kagan and Jackson, 1991; Bodri, 1993; Telesca et al., 1999, 2000a, b).

The identification and quantification of time-clustering behaviour in seismicity was revealed by means of time fractal methods, which allowed us to describe more deeply the temporal fluctuations of earthquakes. The discrimination between Poissonian and clusterized seismic sequences was performed using several earthquake catalogues (Telesca et al., 2001a, b; Telesca and Lovallo, 2009). Space- and depth-variability of time-clustering behaviour was analysed in the seismic catalogues of Italy and Southern California (Telesca et al., 2001c, 2003). The dependence of time-clustering behaviour on the threshold magnitude was investigated in Telesca and Macchiato (2004) and Telesca et al. (2007).

The time-fractal methods used to identify and quantify time-clustering in seismicity are linked with the power spectral density, which is the physical quantity that gives information about the correlation structures of a process. If the power spectrum is flat for all the frequency bands, then the process is memoryless, uncorrelated, and for a point process, like earthquakes, this indicates the presence of Poissonian time dynamics; while if the power spectrum decreases with the frequency as a power law, the process is time-clusterized; the power-law exponent, called scaling exponent, identifies and quantifies the strength of inner time-correlations.

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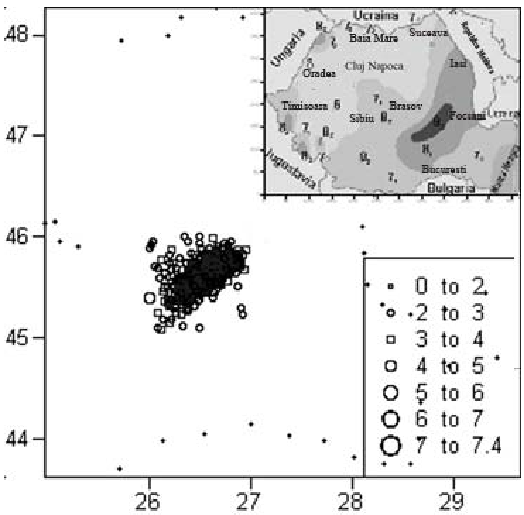

Fig. 1. Spatial distribution of the sub-crustal earthquakes of the Vrancea zone for the period 1978–2008.

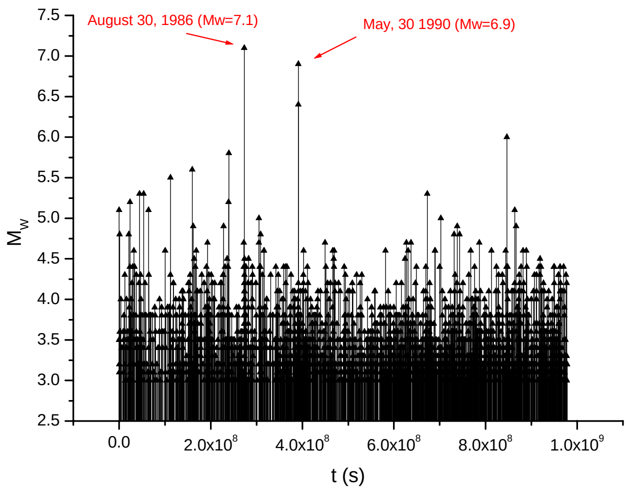

Fig. 2. Temporal distribution of the sub-crustal seismicity of Vrancea for the period 1978–2008. The two arrows indicate the occurrence of the largest shocks.

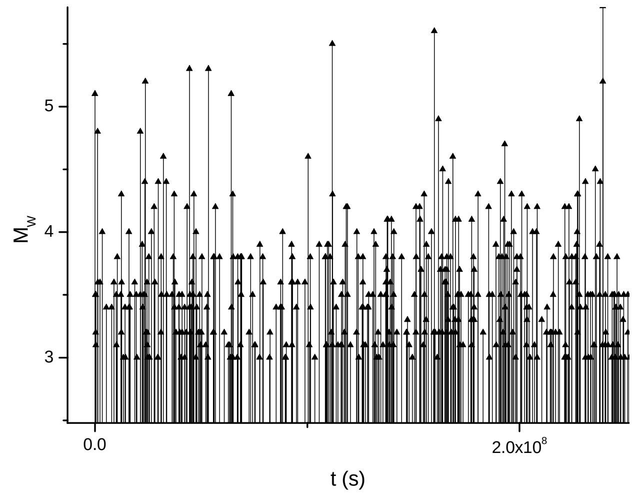

Fig. 3. Enlargement of a portion of Fig. 2.

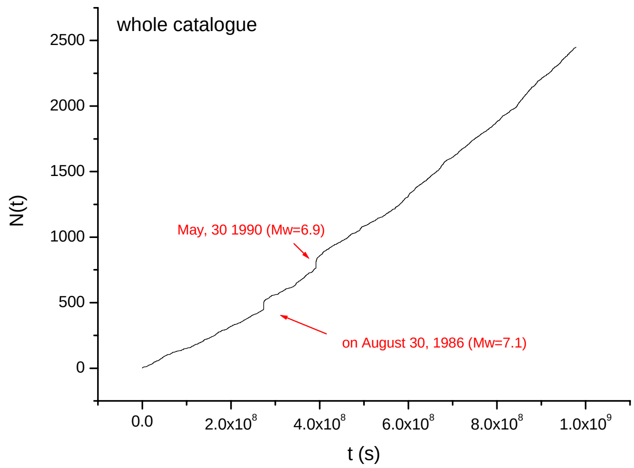

Fig. 4. Cumulative number of earthquakes versus time of occurrence for the full catalogue.

In the present study, the time-clustering behavior of the 1978–2008 sub-crustal seismicity of the Vrancea area is performed. The paper is structured as follows: the section Study area describes the seismicity of the Vrancea area; the section Methods and Data analysis presents the Allan Factor method and the results obtained, analyzing the full and the aftershock-depleted catalogues of Vrancea; the section Conclusions summarizes the main findings of the present study.

2 Study area

From the viewpoint of global tectonics, the Alpine-Mediterranean orogenic region, with a northern branch (Alps, Carpathians, Balkans) and a southern branch (Atlas, Algerian Tell, Apennines, Dinarides, Hellenide, South Caucasus), is a mountainous system formed after the continent-continent type collision between the African, Eurasian and Arabian lithospheric plates, which lies from Gibraltar to Indochina (Larson and Pittman, 1985; Bala, 2000; Popa, 2007; Sandulescu, 1984; Rebai et al., 1992; Dewey et al., 1973; Spencer, 1988). At a regional level, the folded belt of the Alpines and the Balkans constitutes the complex geological structure of the Carpathian Arc, within which the seismic area of Vrancea is included. The seismotectonic mechanisms of the Vrancea zone is interpreted as

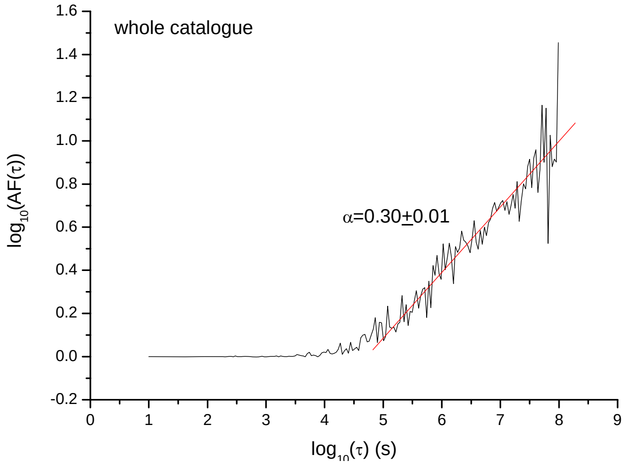

Fig. 5. Allan Factor curve for the full catalogue.

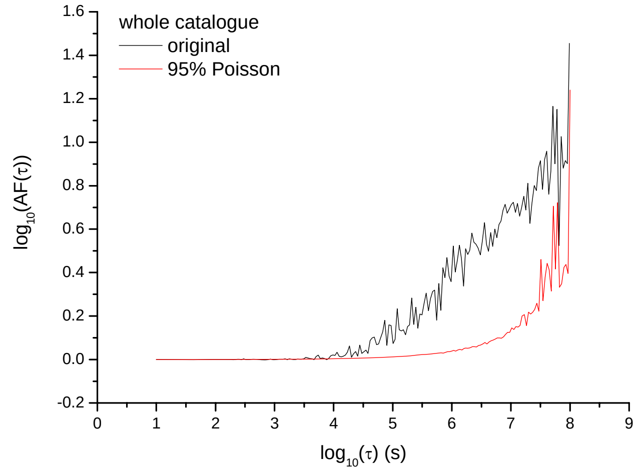

Fig. 6. Comparison between the AF curve for the full catalogue (black line) and the 95 % confidence curve (red line) obtained by means of generation of 1000 Poissonian sequences.

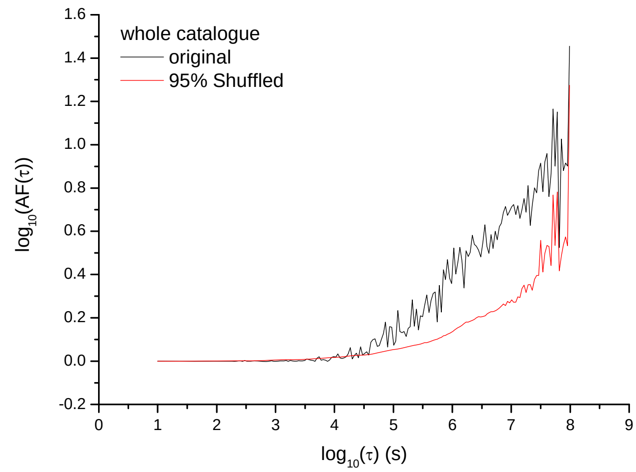

Fig. 7. Comparison between the AF curve for the full catalogue (black line) and the 95 % confidence curve (red line) obtained by means of generation of 1000 randomly shuffled sequences.

a continental subduction (Bala, 2000; Popa, 2007; Enescu, 2001), by means of two general models: (i) a classic Benioff zone, and (ii) a weak slab.

Studies of global seismicity have indicated that the rate of the seismic activity of the Carpathian Arc comprises 1/1500 of the global one (in term of energy) and seismic power approximately $2.5 \pm 0.1 \times 10^{14}$ J yr (Sandu, 2009) or 3.5×10^{14} J yr (Radu and Polonic, 1982). Approximately 93 % of the released energy in the Carpathian region is due to the Vrancea area, where 95 % of the seismicity is of the sub-crustal type ($h \geq 60$ km).

The spatial distribution of the sub-crustal seismic epicenters is highly concentrated (Fig. 1), with 89 % of the Vrancea events located within $1° \times 1°$ square (Radu and Polonic, 1982) and depth ranging between 60 and 170 km (Riznichenko et al., 1976), with maximum depth around 200 km (Oncescu, 1999). The depth distribution shows a maximum between 130 and 150 km (Radu and Polonic, 1982).

3 Methods and data analysis

We analysed the sub-crustal earthquake sequence occurring in the Vrancea area. We considered all the events that occurred between 1978 and 2008 with a depth of $h \geq 60$ km and magnitude of $M_w \geq 3.0$. The threshold magnitude of 3.0 was suggested by Oncescu et al. (1999) as the completeness magnitude for the considered period. The temporal distribution of the analysed seismicity is shown in Fig. 2; in particular two large events that occurred during the observation period, on 30 August 1986 ($M_w = 7.1$) and 30 May 1990 ($M_w = 6.9$). Looking at a portion of the series (Fig. 3), the sequence appears clusterized in time because the events are not homogeneously distributed on time.

The typical cumulative number of events $N(t)$ versus time t is shown in Fig. 4; the local rate (local slope) is not constant, contrary to a Poisson process; in fact, clearly visible are the two jump-like features associated with the two largest events (indicated by the arrows), superimposed to nonlinear trend.

The Allan Factor (AF) is applied to detect correlations in the sequence of the earthquake counts. Dividing the time axis into equally spaced contiguous windows of duration τ, and denoting with $N_k(\tau)$ the number of events falling into the k-th window, the Allan Factor is defined as $\mathrm{AF}(\tau) = \frac{<(N_{k+1}(\tau) - N_k(\tau))^2>}{2<N_k(\tau)>}$, where <..> indicates expectation value. If the sequence of earthquakes is clusterized in the time domain, then $\mathrm{AF}(\tau)$ behaves as a power-law function,

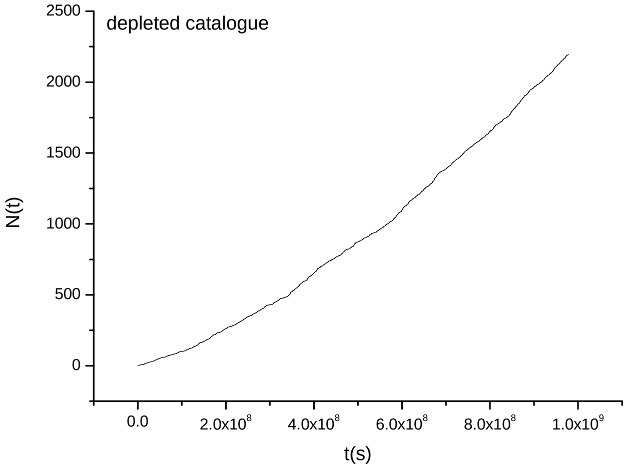

Fig. 8. Cumulative number of earthquakes versus time of occurrence for the aftershock-depleted catalogue.

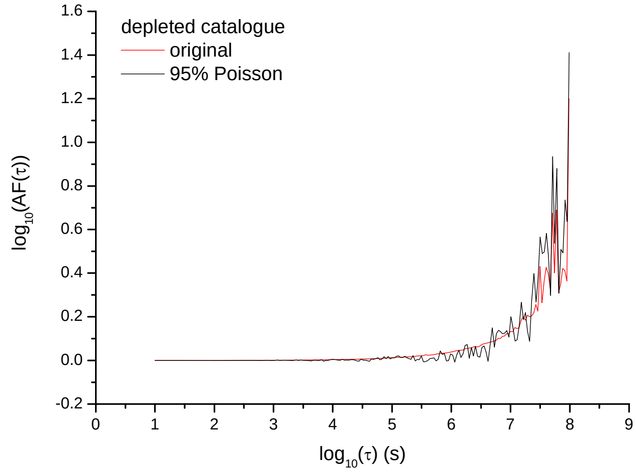

Fig. 10. Comparison between the AF curve for the aftershock-depleted catalogue (black line) and the 95 % confidence curve (red line) obtained by means of generation of 1000 Poissonian sequences.

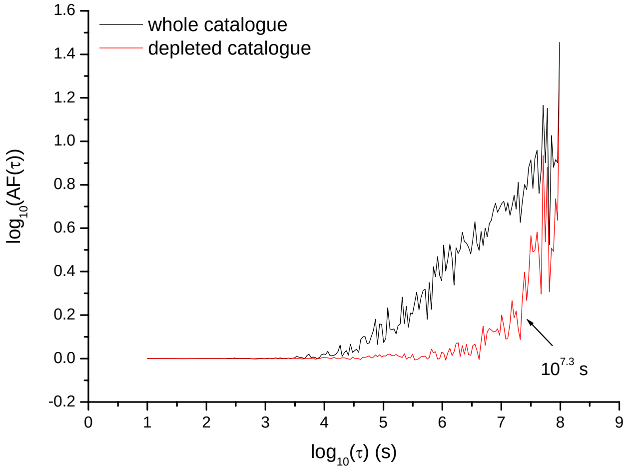

Fig. 9. Comparison between the AF curves for the full and the aftershock-depleted catalogues.

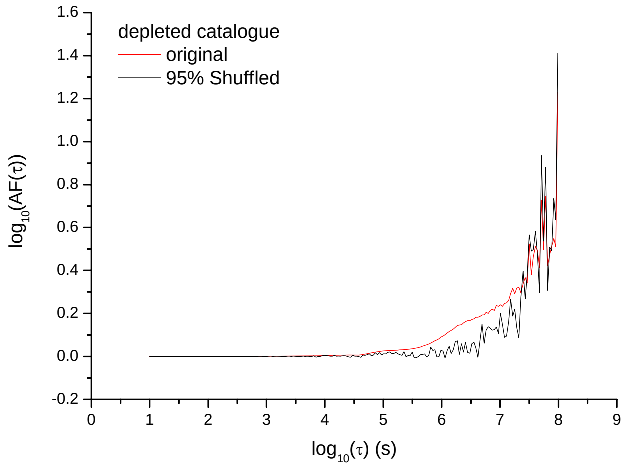

Fig. 11. Comparison between the AF curve for the aftershock-depleted catalogue (black line) and the 95 % confidence curve (red line) obtained by means of generation of 1000 randomly shuffled sequences.

$\mathrm{AF}(\tau) \propto \tau^{\alpha}$ (Thurner et al., 1997), and the fractal exponent α can be estimated by the slope of the line that fits the curve in its linear range; for a hypothetical Poissonian earthquake sequence, the AF is approximately near unity for all timescales τ, with $\alpha \approx 0$.

Figure 5 shows the AF of the seismic sequence recorded in the investigated area for timescales τ from 10 s to about 3 yr; the upper timescale corresponds approximately to the 1/10 of the entire period; higher timescales would lead to misleading results for the poorer statistics. The AF plot suggests the presence of time-clustering behavior, because it increases with linear form for $\tau > 10^5$ s in bilogarithmic scales. The estimate of the scaling exponent in such a timescale range is ∼0.3. The cutoff timescale 10^5 s is the so-called fractal onset time (Thurner et al., 1997) and indicates the lower timescale from which clustering behavior can be detected and quantified. The early flatness of up to about 10^4 s indicates a Poissonian-like behavior of the sequence for the small timescales. The intermediate timescale region between 10^4 s and 10^5 s can be considered as a "transfer" timescale region between the two opposite behaviors, from Poissonian to clusterized dynamics.

In order to check whether the AF curve is significantly distinguished from that obtained by Poissonian sequences characterized by identical mean intervent time and identical number of events, we generated 1000 Poissonian sequences. To each simulated sequence the AF was applied. For each timescale the 95th percentile among the AF values for that timescale was calculated. The final 95 % confidence AF curve was then given by the set of the 95th percentiles. The AF curve is significantly different from those obtained by the Poisson surrogates for $\tau > 10^4$ s, therefore, the scaling behavior of the seismic cluster is significantly non Poissonian (Fig. 6).

In order to check whether the scaling behavior of the sequence is due to the shape of the probability density function of the interevent times or to the their orderings, we shuffled the interevent intervals 1000 times, and for each shuffle we calculated the AF curve. The 95 % confidence AF curve for the shuffles was calculated as above (Fig. 7). This curve is lower than the AF curve of the original sequence, and this indicates that the scaling behavior is due to the specific ordering of the interevent intervals.

In order to check whether the time-clustering behavior of the sequence depends on the aftershock activation that followed the two largest events that occurred during the observation period producing a sharp increase of seismic activity (Fig. 4), we analysed the aftershock-depleted catalogue. A possible method to eliminate the aftershocks is to use a space-time rectangular or circular window, dependent on the magnitude of the mainshock (Gardner and Knopoff, 1976). This method has been improved by means of a dynamic aftershock clustering algorithm, which considers the peculiarity of each main shock concerning the extent of the aftershocks in space and time (Reasenberg, 1985). The method of Reasenberg is based on a physical basis, which considers each earthquake capable of generating an alteration of the surrounding stress field that may trigger a further seismic event, which nucleates in its surroundings a modified stress field. The areal and time extent for which the event can trigger a following event is called interaction zone of the earthquake, whose length scale is proportional to the source dimension, and the temporal scale is determined with a probabilistic model based on Omori's law. Thus, we applied the Reasenberg's algorithm to remove aftershocks from the investigated catalogue. Figure 8 shows the cumulative number of the earthquakes vs. the occurrence time for the depleted catalogue, which does not present sharp jump-like increases of the seismic activity (Fig. 8). We applied the AF method to this aftershock-depleted catalogue and the results compared with those obtained for the whole catalogue (Fig. 9). It is clearly visible that the whole catalogue presents a clustering behaviour stronger than that revealed by the depleted catalogue, whose AF curve is approximately flat for almost all the timescales up to about $10^{7.3}$ s, which can be considered as the fractal onset time for the depleted sequence. We checked the significance of our results applying the two methods of generation of surrogate series (Poissonian and shuffled), as we did for the whole catalogue. The 95 % confidence AF curves over 1000 Poissonian (Fig. 10) and shuffled (Fig. 11) surrogate series is almost overlapping with the AF curve of the original depleted catalogue. This indicates that the depleted catalogue is quasi-Poissonian and that its scaling behaviour depends mainly on the shape of the probability density function of the interevent times and not on their orderings.

4 Conclusions

The time-clustering behaviour of the 1978–2008 sub-crustal seismicity (depth larger than 60 km) of the Vrancea region was analysed by means of the Allan Factor method, which allows us to detect and quantify time-clustering in a temporal point processes. The full catalogue and that depleted by the aftershocks that followed the two largest earthquakes occurring on 30 August 1986 ($M_w = 7.1$) and 30 May 1990 ($M_w = 6.9$) revealed that significant time-clustering is mainly due to the aftershock activation than to the background seismicity. The findings of the present study contribute towards better characterization of the time dynamics of the seismicity of Vrancea.

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