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A ten-year study (2008-2017) of short-term clustering features of Greek Seismicity

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Studying the clustering features of seismicity both in space and time is one of the most important factors of earthquake forecasting. Earthquake occurrence exhibits short and long term clustering (Kagan and Jackson, 1991; Dieterich, 1994) due to the physical processes related with seismogenesis (e.g. fault interactions and heterogeneity). Focusing on short-term clustering, the seismicity can be considered as the summation of background seismicity of spontaneous earthquakes and triggered one, which dominated by foreshocks, mainshocks and aftershocks or swarm like excitations. The time span of such clustering typically ranges from several months to few years and is spatially distributed mostly around a strong event (e.g. a mainshock) of the order of a few km.

Earthquake occurrence can be represented as a stochastic point process in which the occurrence rate, λ, gives the instantaneous probability of event occurrence (Daley and Vere-Jones, 2003). Despite the fact that many purely temporal models are developed, only few spatiotemporal ones have been proposed, namely the ETAS (Ogata, 1998; Console and Murru, 2001), the EEPAS (Rhoades and Evison, 2004), the double branching model (Marzocchi and Lombardi, 2008). The Epidemic Type Aftershock Sequences (ETAS) model is the most popular one for such studies and is suggested as the best for describing the short-term seismicity (Console *et al.*, 2007).

The spatiotemporal ETAS model, which is an extension of the temporal ETAS model (Ogata, 1988), is formulated as follows:

$$\lambda(t,m,x,y|H_t) = \lambda(t,x,y|H_t) f_m =$$
$$= \left[\mu \cdot u(x,y) + \sum_{T_i<t} \frac{k \cdot e^{\alpha(M_i - M_c)}}{(t-T_i+c)^p} \frac{c^i_{d,q,\gamma}}{\left[r_i^2 + d^2 e^{2\gamma(M_i - M_c)}\right]^q}\right] f_m \quad (1)$$

where *u(x,y)* is the spatial probability density function (pdf) of background events, $\{\mu, k, p, c, \alpha, d, q, \gamma\}$ are the 8 parameters to be estimated, r_i is the distance between location *(x,y)* and the epicenter of the i^{th} event (in kms), $c^i_{d,q,\gamma}$ is a normalization constant, depending on parameters $\{d, q, \gamma\}$, M_c is the completeness magnitude of the given dataset and f_m is the magnitude pdf representing the Gutenberg-Richter law, given by:

$$f_m = \beta e^{-\beta(M - M_c)} \quad (2)$$

with $\beta = b\ln(10)$ linked to the b-value of the dataset.

Using this model, a thorough study of the clustering features of crustal seismicity ($h \leq 50$ km) in Greece is conducted in both space and time during the period from 2008 up to 2017, when 17 strong events with $Mw \geq 6.0$ occurred. The earthquake catalog is compiled based on the recordings of the Geophysics Department of Aristotle University of Thessaloniki (GD-AUTh). With a completeness threshold of M_c=3.5 and *b*-value equal to 1.17 (*b*=1.17), 7455 events are comprised in the data set (Figure 1) provoking the detailed analysis of the spatiotemporal characteristics of short – term clustering behavior.

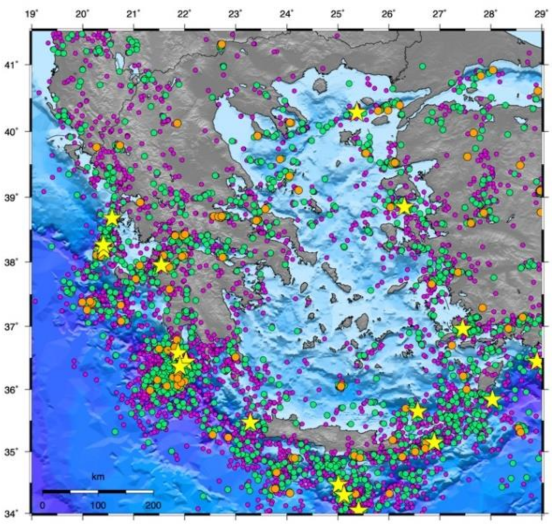

Figure 1. Epicentral distribution of crustal ($h \leq 50$km) seismicity with $M_c \geq 3.5$ of the broader Greek territory during the period 2008 to 2017. Small magenta, moderate green and large orange circles depict earthquakes in the magnitude ranges $3.5 \leq M < 4.0$, $4.0 \leq M < 5.0$ and $5.0 \leq M < 6.0$, respectively. Yellow stars depict the $M \geq 6.0$ events.

The estimation of the model parameters is made via the MLE technique using a simulated annealing approach proposed by Lombardi (2015) implemented in the software package SEDA (Lombardi, 2017), dividing the study area by a regular grid of 0.2^{o}x0.2^{o}, resulted in 2080 cells in total. The meaning of estimated parameters is discussed and interpreted in connection with the physical processes related with strong earthquakes occurrence. The model is then tested by applying a residual analysis procedure. The initial estimated model including the entire dataset, underestimates the observed seismicity, while it seems to be unstable, leading to an explosive one (in other words a model with infinite decay rate). Specifically, the underestimation is observed during 2008, when five $Mw \geq 6.0$ occurred. Excluding the events in 2008, the estimated model exhibits good agreement with the observed seismicity. In order to develop a stable model including the 2008 seismicity, a different set of constrains concerning the 8 parameters estimation is adopted.

Regarding the final suggested model, the classification between background and triggered events is made by measuring the contribution of each class to the total seismicity using the stochastic declustering method (Zhuang *et al.*, 2002). Individual earthquake sequences occurred in different tectonic regimes are identified and compared using the stochastic reconstruction method (Zhuang *et al.*, 2002). The stationarity of the background seismicity rate is investigated for these different areas along with the recognition of seismicity bursts or quiescence before and after major earthquakes. The present model can be considered as a reference one for the Greek territory with many potential applications including declustering the Greek earthquake catalog for time independent studies, identification of possible triggering patterns and forecasting of future strong earthquakes.

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