A study of earthquake clustering in central Ionian Islands through a Markovian Arrival Process

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INTRODUCTION

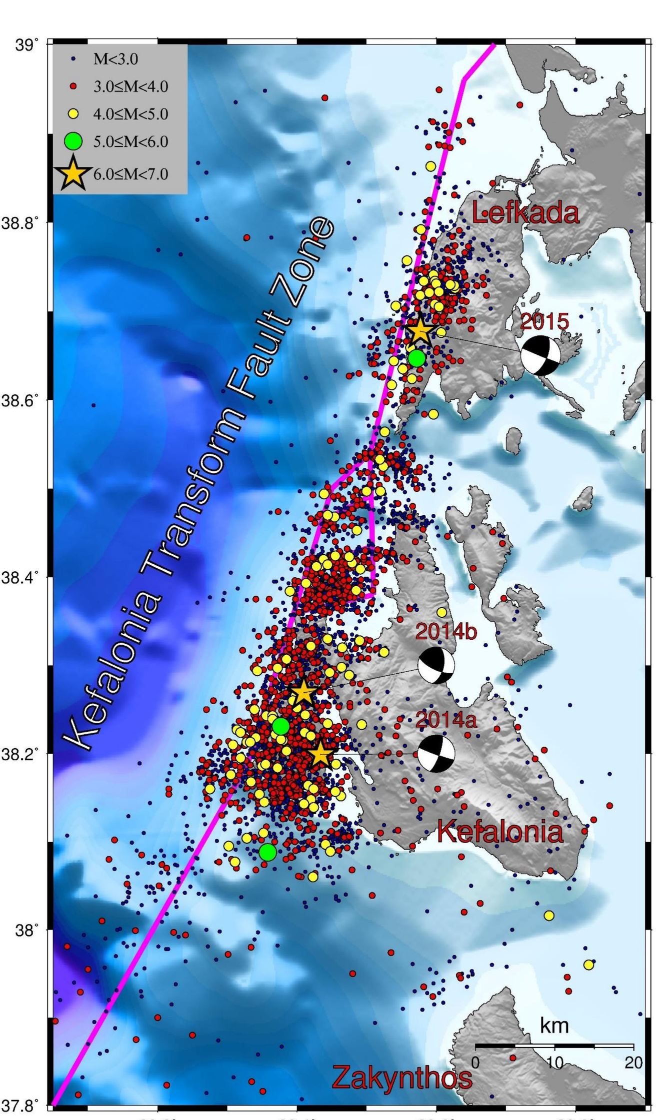
The study of earthquake clustering can provide crucial information on the seismogenesis properties of a region. The seismicity may then be separated into background and clustered one, which is an important step for short-term earthquake forecasting.

Several declustering algorithms exist with different underlying assumptions [1-4]. In our study, we assume that the prevailing parameter to separate the background seismicity from seismic excitations are the temporal variations of the seismicity rate.

The method applied for this purpose is based on a stochastic point process, the Markovian Arrival Process (MAP) [5], that captures the temporal evolution of both mainshock-aftershock sequences and swarms combined with a density-based spatial clustering algorithm of applications with noise (DBSCAN) [6] that separates events close in space from sparse seismicity (low density areas).

The efficiency of the method is tested in the area of Central Ionian Islands, Greece, which is an active boundary characterized by remarkably high seismic activity, with frequent strong mainshocks ($M \geq 6.0$) and under continuous monitoring by a dense seismological network.

STUDY AREA



- Spatial distribution of 4360 events with $M_c = 2.4$ in Central Ionian Islands from Jan 2011 to Aug 2016
- Three strong ($Mw \geq 6.0$) main shocks occurred during this period, the 2014 Kefalonia doublet (Mw6.1 and Mw6.0) and the 2015 Lefkada $Mw6.5$ earthquake

MAP AND DBSCAN FORMULATION

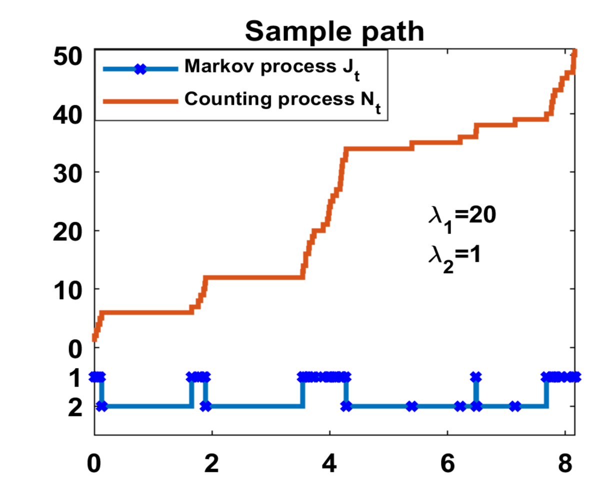
MAP: Bivariate stochastic point process $(N, J) := (N_t, J_t)_{t \in R^+}$

- N_t counting process → number of events in (0,t]
- J_t Hidden Markov process, E={1,…,m} → unobserved states
- Model parameters:
  $\boldsymbol{D}_0 = -diag(\lambda_1, \dots, \lambda_m)$ and $\boldsymbol{D}_1 = \{q_{ij}\,(1)\}_{(i,j \in E}$

➢ $q_{ij}(1)$ → transition rate from i to j with earthquake occurrence

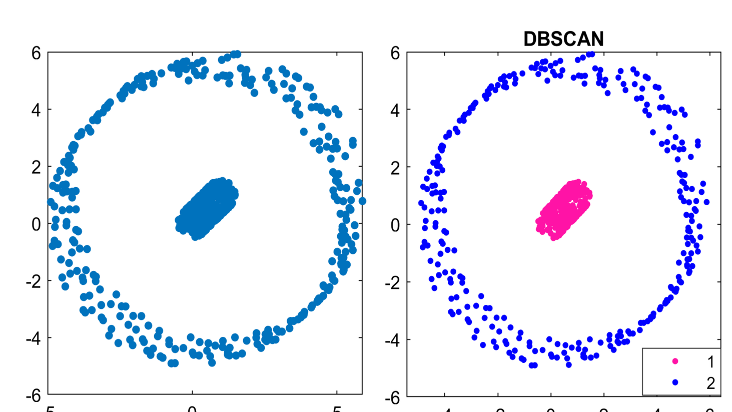
➢ $\lambda_i = \sum_{j=1}^{m} q_{ij}\,(1)$ → distinct occurrence rate at state $i \in E$

- $P(J_{t_k} = i) = \frac{\boldsymbol{f}[k]_i \cdot \boldsymbol{b}[k]_i}{L(\boldsymbol{\theta}/T)}$, $\boldsymbol{f}$[k], $\boldsymbol{b}[k]$ forward-backward vectors and $L(\boldsymbol{\theta}/T)$ likelihood value



Sample path of a MAP with $\lambda_1 = 20$ and $\lambda_2 = 1$

DBSCAN: Density-based algorithm separates
i) Highly concentrated points in arbitrary shape
ii) Low density areas-Noise
Two parameters:
Distance threshold ϵ →how far do we search for neighbors
Density level minPts →minimum number of neighbors

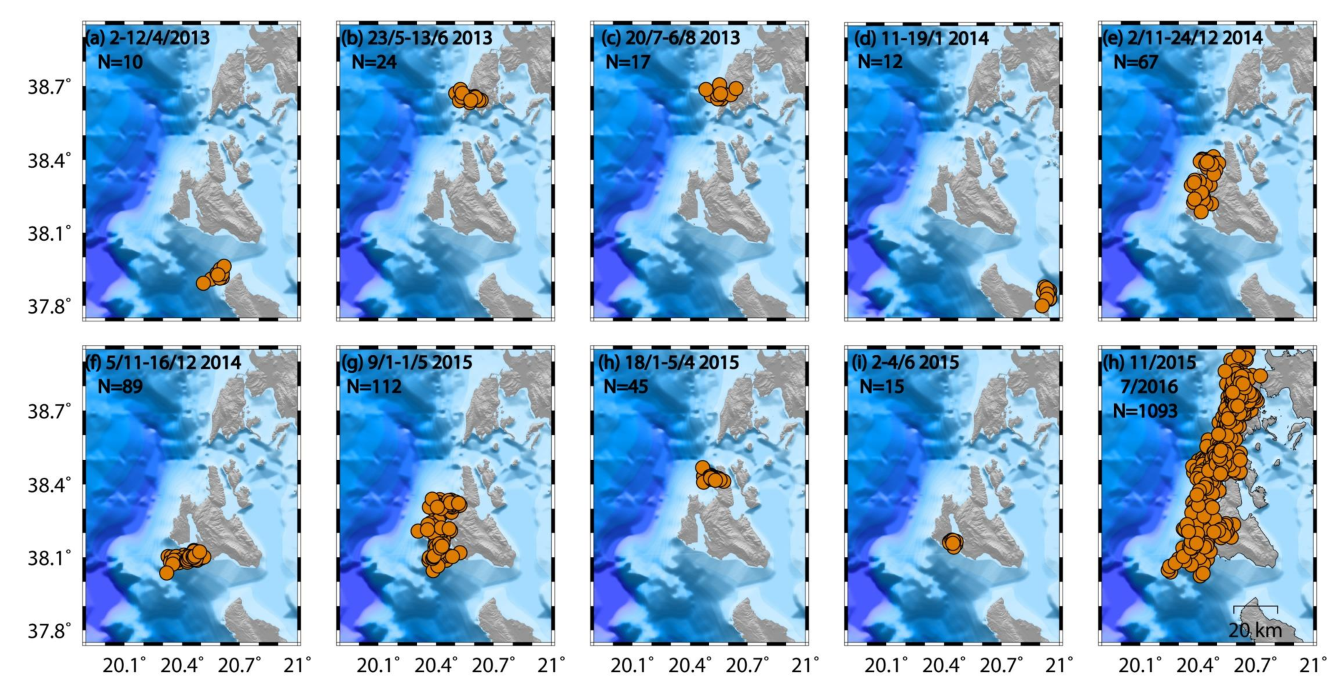


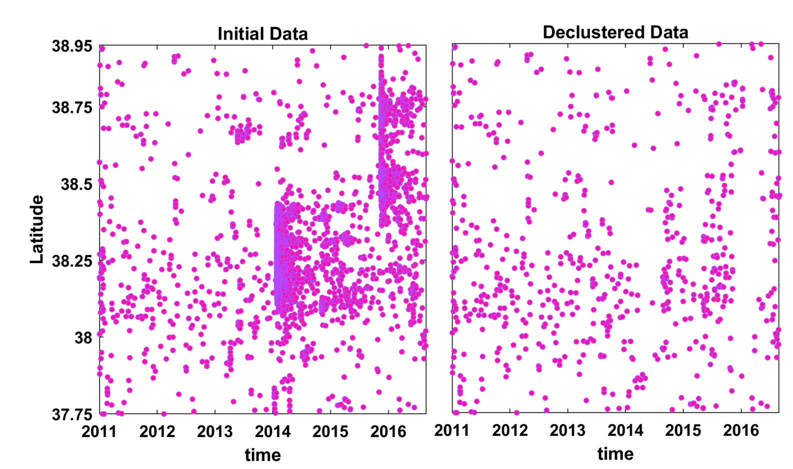
Implementation of DBSCAN

METHODOLOGY

- Definition of the study area, S, time interval, T and completeness magnitude M_c
- Estimate $\boldsymbol{\theta} = \{\lambda_1, \dots, \lambda_M, q_{ij}(1)\}$ → EM algorithm [7]
- Optimal number of states → AIC or BIC
- Estimate seismicity rate in time → Reveal hidden states $J_{t_k} = arg \max_{1 \leq i \leq M} P(J_{t_k} = i/T)$ [8]
- Primary clusters → Events with $\lambda_{t_k} \geq \lambda_{thr}$
- Merging clusters → Events $\pm dt$ probably merged with background seismicity
- Final clusters → Implement DBSCAN and discard low density events

APPLICATION TO CENTRAL IONIAN ISLANDS



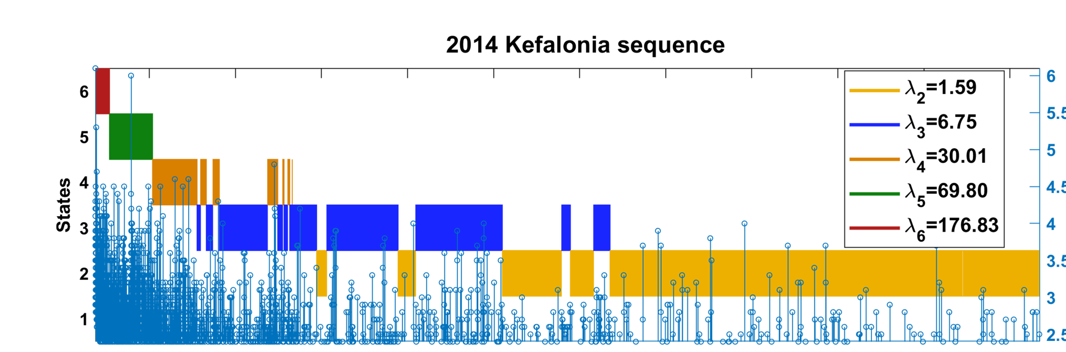


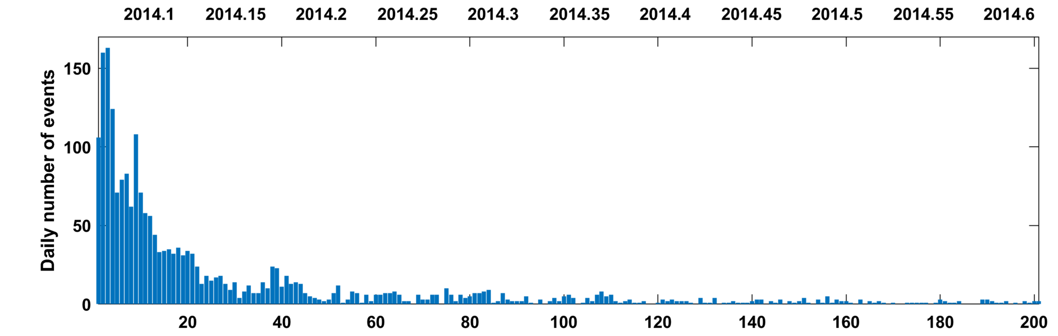
Top: Clusters with minimum number of events equal to 10 for different time periods

Left: Spatio-temporal evolution of the initial data set and the declustered one

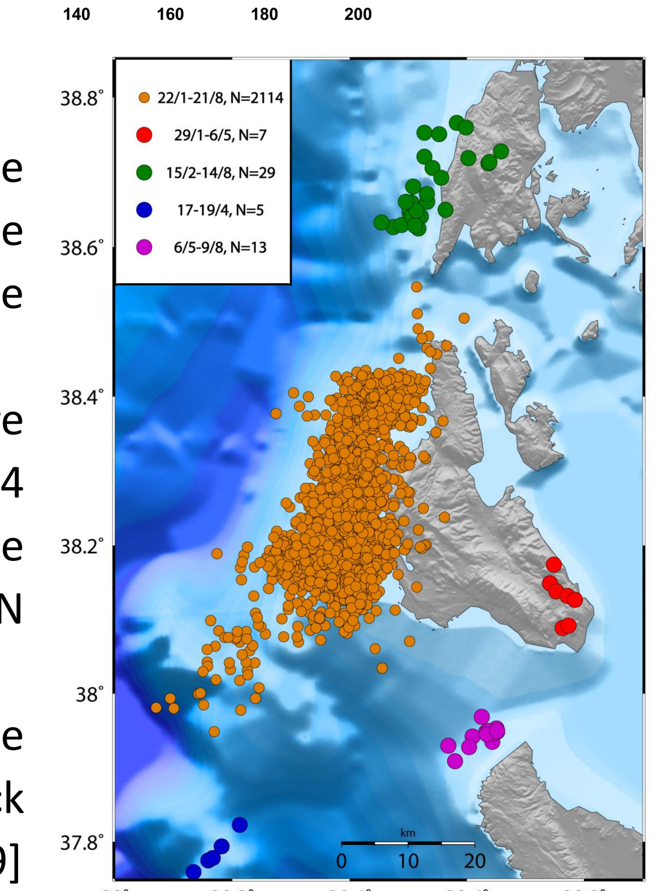
Major clusters are revealed

Clustered events	# Clusters
3687 (84%)	22





- *Top*: Temporal evolution of the 2014 Kefalonia sequence according to the states of the model
- *Right*: Final clusters which are associated with the 2014 Kefalonia sequence after the implementation of the DBSCAN algorithm
- Results are consistent with the manually identified aftershock sequence of the 22 first days [9]



CONCLUSIONS

- Identified seismic excitations consistent with ones that have been derived by manually studied aftershock sequences, like the 2014 Kefalonia doublet ($Mw6.1$ and $Mw6.0$)
- Clustered component of seismicity is dominant in Central Ionian Islands due to the large seismic energy release of the two main sequences (2014 Kefalonia and 2015 Lefkada earthquakes)
- Main clusters are identified according to the spatiotemporal patterns of the background seismicity

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