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Earthquake clusters in Corinth Gulf, Greece: Identification through a Markovian arrival process (MAP)

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Clustering of earthquakes both in time and space is a vital aspect of seismicity, which provide information on the earthquake dynamics. For the study of the seismicity patterns and clustering characteristics in Corinth Gulf, Greece, we applied a Markovian Arrival Process (MAP) (Neuts, 1979), which is a temporal bivariate point process $(N_t, J_t)_{t\in R^+}$, with an intensity rate driven by a Markov one with unobservable states. The counting process, N_t, counts the number of events in a time interval $[0, t)$, which are associated with the evolution of the underlying Markov process J_t, at time $t \geq 0$; that is, the hidden states indicate the seismicity rate. The parameters of the MAP are estimated through an EM algorithm (Dempster *et al.*, 1977), which is iterative in that at each step it computes the log-likelihood function and reaches a local maximum after a predefined number of iterations or a convergence criterion. We followed a special structure of the rate matrices (Horvath and Okamura, 2013) where transitions among the hidden states are allowed only when arrivals are taken place. The information criterion of Akaike (Akaike, 1974) is used to determine the number of distinct seismicity rates that characterize each earthquake catalog. Residual analysis is applied to assess the goodness-of-fit of the model (Ogata, 1988), and the most likely sequence of the hidden states under which the observations occurred is computed via a local decoding algorithm. For the implementation of the algorithm the forward-backward equations are used (Mac Donald and Zucchini, 1997) and the robustness of the method is verified on synthetic catalogs where the hidden path is known. MAP is applied in the Corinth Gulf, Greece, which is a region with high seismic activity. In the study, we used the data from the catalog compiled by the Geophysics Department of the Aristotle University of Thessaloniki (Permanent Regional Seismological Network (1981)). The study area is divided in the eastern and western parts, based on seismotectonic criteria and the model is tested for different periods and magnitude thresholds in both subareas. A complete cluster analysis of the revealed path of the hidden states (Figures 1 and 2) is given for the 135 and 139 earthquakes with $M \geq 4.5$ that occurred from 1964 to 2017 in the eastern and western parts, respectively, and the correspondence of the hidden states to the major earthquake sequences is addressed. Three states seem sufficient to describe the temporal fluctuations of earthquake occurrences for both subareas, with the lowest seismicity rate corresponding to the first one (state 1). The third state corresponds in most cases to main shocks and their immediate aftershocks. In the western part, 10 to 13 events with $M \geq 5.5$ occurred in state three, which suggests that an aftershock with $M \geq 4.5$ is expected during next hours. Our results show that the model can capture the behavior of active seismic periods revealing seismic sequences and swarms, as well periods of seismic quiescence and might be introduced as a model for change point detection able to reveal seismic clusters.

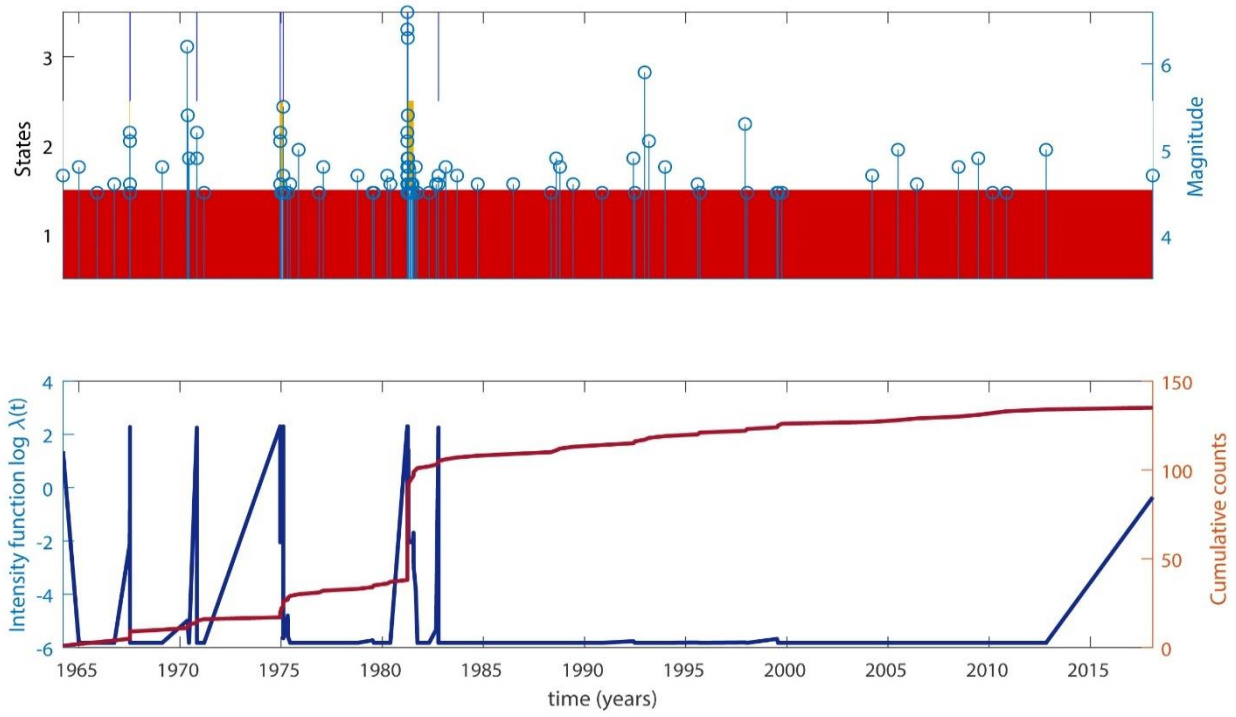

Figure 1. *Top:* Most probable state of the underlying process, J_t, of the eastern subarea, for magnitudes, $M \geq 4.5$. *Bellow:* Logarithm of the intensity function of the counting process, N_t, and cumulative number of the events.

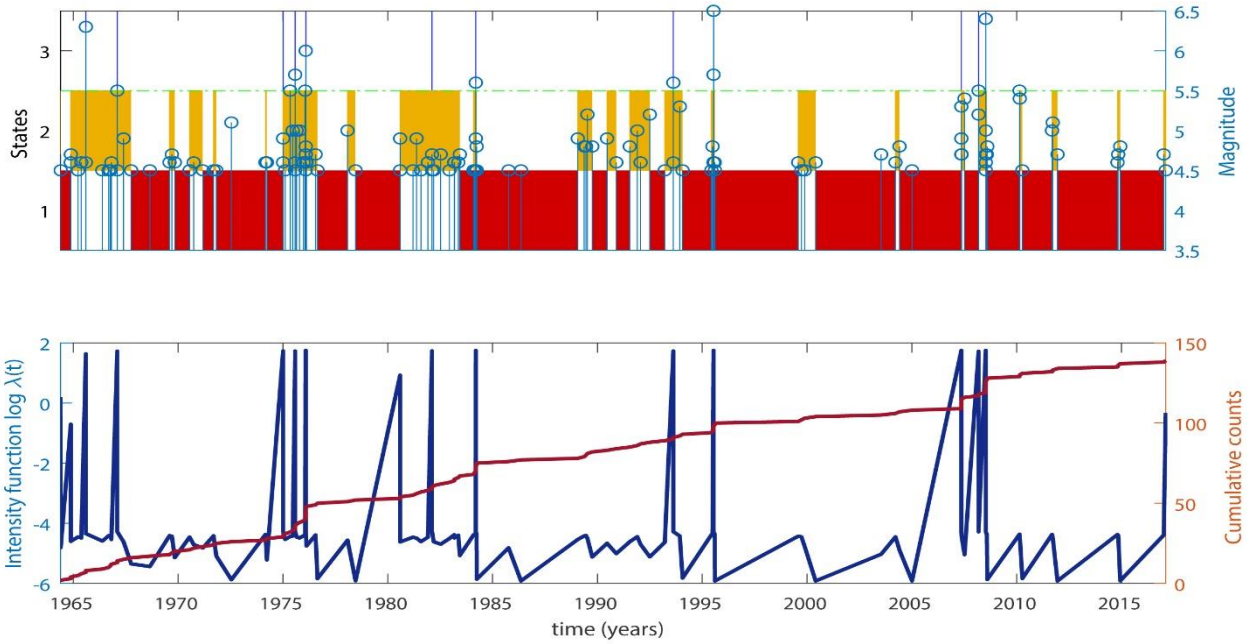

Figure 2. *Top:* Most probable state of the underlying process, J_t, of the western subarea, for magnitudes, $M \geq 4.5$. *Bellow:* Logarithm of the intensity function of the counting process, N_t, and cumulative number of the events.

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