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Physics-based simulation of spatiotemporal patterns of earthquakes in the Corinth Gulf fault system

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Introduction

In the last decade new and more complex physics-based simulators were developed and have acquired a growing interest as a tool for comprehension and testing of seismic process models. The earthquake simulators differ in the type of methodology developed within them and for the geometry type of the grid used in the fault model. A recent paper by Field (2019) supports the usefulness of physics-based earthquake simulators for improving overall testing procedures for earthquake forecasting.

Here we apply an earthquake simulation algorithm of new generation and study its potential for modelling the long-term spatiotemporal process of strong earthquakes preparation. The algorithm of our simulator was initially introduced by Console et al. (2014), and successively modified by Console et al. (2017, 2018). In this improved version a specific seismogenic structure is modelled by quadrilateral faults constituted by thousands of cells with sides of 1 km or less. Note that modelling the seismic sources by numerous segments of rectangular or trapezoidal shape is just a convenient tool for the simplicity of the algorithm used in the physics-based simulator code, but definitely does not limit a rupture to expand beyond the edges of such segments.

The physical model on which the latest version of our simulation algorithm is based also includes, besides tectonic stress loading and static stress transfer as in the previous versions, the Rate & State constitutive law. The simulator code needs relatively modest computer resources and is capable for simulating tens of thousands of years of seismic activity producing catalogues of tens of thousands of events in a wide magnitude range. The resulting synthetic catalogues exhibit typical magnitude, space and time features, which are comparable with those of real observations.

In this study we applied the simulator code to a physical model for the Corinth Gulf (Greece) fault system, a well-known seismic structure about 100 km long, where several earthquakes of magnitude larger than 6.0 occurred in the last few centuries. This structure is typically modelled after being subdivided into eight major fault segments characterized by different slip-rates, which can rupture either separately or simultaneously (Console et al., 2015). The results of this simulation provide interesting inferences on the spatiotemporal properties of seismic activity in the study area. In particular, the recurrence time of the larger events and their spatial relation are investigated.

Application to the seismicity of the Corinth Gulf fault system

By means of a set of preliminary trials, the values of the free parameters characterizing the simulation algorithm were set up in order to obtain a synthetic catalogue reproducing realistic features of the real observations, including the *b*-value of the frequency-magnitude distribution. The simulation was run over a period of 100 kyr, preceded by a warm up period of 10 kyr not used in the output catalogue. Some results of the synthetic catalog are reported in Table 1.

Table 1. Features of the 100,000 yr synthetic catalogue in the Corinth Gulf fault system

Number of earthquakes of $M \geq 4.0$	158,923
Number of earthquakes of $M \geq 5.0$	68,321
Number of earthquakes of $M \geq 6.0$	3,931
Number of earthquakes of $M \geq 6.5$	632
Maximum likelihood *b*-value ($M \geq 4.5$)	0.80
Largest magnitude M_{max}	6.81
Annual seismic moment M_0 ($M \geq 4.0$)	2.66E+17 Nm/yr
Number of earthquakes of $M \geq 6.0$ rupturing only one segment	2,365
Number of earthquakes of $M \geq 6.0$ rupturing at least two segment	1,566
Largest number of segments ruptured in one earthquake of $M \geq 6.0$	5

Recurrence of large magnitude earthquakes in the synthetic catalogue

We examined the statistical features of the synthetic catalogue referring to the long term series of large magnitude earthquakes for some specific seismogenic faults of the study area. In order to carry out a statistical analysis of the earthquake recurrence intervals, we need a quantitative, even if somehow arbitrary, definition to identify in a seismic catalogue the events to which we want to apply such analysis. For a more in-depth discussion of this issue, we refer to Field (2015) addressing the "recurrence of what?" question.

There could be two ways for associating earthquakes to specific segments. These ways can be termed either "nucleation" or "participation" (Parsons et al., 2018). Once we have selected a segment to be studied, by the nucleation criterion we take only earthquakes encompassed in the considered segment. In this case, each earthquake can be associated to one segment only, even if it has substantially ruptured more than one segment. This criterion may lead to underestimation of the hazard assessment of a specific site, because a very large earthquake rupturing a segment close to that site might be ignored in the analysis, if its hypocenter was located into a different source. Moreover, we should consider the fact that frequently seismic catalogues provide the hypocentral coordinates of a large earthquake outside any segment reported in the adopted geological model.

By the participation criterion we associate to a specific segment all the large earthquakes that have ruptured a substantial part of this seismic source. In this way, any single earthquake can be counted more than once in the recurrence analysis of different sources. The participation criterion can be applied to the synthetic catalogue generated by our simulation algorithm because the output file contains the number of cells ruptured by each earthquake for any segment.

In this analysis, we have adopted the participation criterion by applying the following empirical rules: 1) a magnitude threshold of 6.0 for the considered earthquake is assigned; 2) the earthquake is initially assigned to the segment containing the nucleation cell of the earthquake; 3) if the equivalent magnitude estimated by the number of cells ruptured by the earthquake in one of any other segments is larger than the minimum magnitude assigned by rule 1, then this segment can be associated to the same earthquake; 4) if the earthquake ruptured at least 70% of the cells of a segment, then this segment can also be associated to this particular earthquake. In this way, we counted through the whole 100 kyr synthetic catalogue the number of times that a given fault segment has participated in any $M \geq 6.0$ earthquake alone (2,365 times) or jointly with other segments (1,566 times). In six cases, five segments ruptured all together in one single very large earthquake (Table 1).

In order to assess whether the earthquake occurrence time on single segments in the synthetic catalogue behaves either as a Poisson process or it rather exhibits some pseudo-periodical feature, we carried out a statistical analysis of the inter-event times for the entire 100 kyr simulation. The analysis focused on the sources listed in Table 2, which displays the mean inter-event time, the standard deviation, and the coefficient of variation of each analysed segment, for the earthquakes fulfilling the four above-mentioned empirical rules. This Table also reports the results of the difference between the log likelihood computed by the Brownian Passage Time (BPT) renewal model and the Poisson time-independent model ($d\log L$). For the likelihood estimation we adopted the values of Tr and Cv reported in Table 2 for each segment.

Table 2. Statistical parameters obtained for some sources of the 100,000 yr synthetic catalogue associated to earthquakes of $M \geq 6.0$

Segment Number	T_r (yr)	σ (yr)	C_v	$d\log L$
S01 (Psathopyrgos)	169.2	108.4	0.64	208.5
S02 (Aigion)	172.9	124.1	0.72	173.6
S05 (Xylokastro)	106.6	49.9	0.47	262.0
S07 (Skinos)	226.4	99.3	0.44	172.9

The results reported in Table 2 show a moderate pseudo-periodical behaviour of strong earthquakes in all the selected sources, with a significant over-performance of the renewal BPT model with respect to the time-independent Poisson model. Other tests carried out in a similar way with different magnitude thresholds show that smaller magnitudes exhibit a less periodical and more clustered behaviour.

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