Structural changes in seismic activity before large earthquakes

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Abstract: We try to verify whether significant changes in the seismic activity are identifiable prior to a main shock, by means of statistical tests for structural changes applied to earthquakes models. A panel of models is selected, ranging from zero-inflated Poisson model to temporal and spatio-temporal point processes.

Keywords: seismicity patterns, point processes, structural changes

1 Introduction

As Kanamori (1981) pointed out, "various seismicity patterns before major earthquakes have been reported in the literature". Indeed, there is not uniform empiric evidence about the observed seismic activity in proximity of a relevant earthquake. Leaving aside differing definitions, some kinds of pattern are diffusely identified, sometimes following one another in the same seismic sequence: foreshocks (a large number of small events clustered in the main shock area), quiescence (reduced seismic activity before a large event), precursory swarms (distinct clusters of small earthquakes) and doughnut patterns (a quiet focal area surrounded by a region characterized by intense activity). However, different observations have in common the presence of a change in the seismic activity before a major event. Our aim is to detect these changes by means of statistical tests for structural breaks.

2 Materials and Methods

We choose to focus on the area surrounding the city of L'Aquila to verify the assertion of Papadopoulos et al.(2010). In their analysis of the seismic sequence prior to L'Aquila (Italy) earthquake (Mw 6.3) of 6th April 2009, the authors claim to have observed a change in the seismicity rate (daily number of events).

Data on earthquake events for Italy are publicly available on the website of the Istituto Nazionale di Geofisica e Vulcanologia (INGV). The area is identified as the square with side length of 100 km centered in the conventional coordinates of the city of L'Aquila (Lat. 42.35, Lon. 13.40), corresponding to the Forte Spagnolo.

The simplest way to describe a sequence of earthquake events in statistical terms is to consider the number of occurrences in periods of a certain length (days, weeks, months), which can be described in terms of a Poisson distribution. However, if the selected length is short enough, then a considerable number of periods with no events is present. To model this characteristic, we will refer to a zero-inflated Poisson (ZIP) model, as proposed by Guillas et al. (2010) in their analysis of the relationship between the ENSO and EPR seismicity. The number of events in the i-th period, Y_i, is described as follows:

$$\begin{cases} Y_i \sim 0 & \text{with probability } p \\ Y_i \sim Poisson(\mu) & \text{with probability } 1-p \end{cases} \tag{1}$$

To consider the presence of autocorrelation, neglected by the basic ZIP model, we will also perform time-series analysis, firstly introducing an auto-regressive component.
However, earthquake occurrences are more frequently described by means of point processes. Among this class of models, the most known is the Epidemic-Type Aftershock Sequence (ETAS) proposed by Ogata (1988). The first version of the model did not consider spatial coordinates, which were introduced in successive works (e.g. Ogata 1998). In this model, every single event is susceptible to produce an aftershock sequence. The occurrence rate of events, that is the conditional intensity λ, is therefore given by background seismicity μ and aftershocks, which are a function of magnitude (M) and of spatio-temporal $(x; y; t)$ coordinates of the triggering events:

$$\lambda(t,x,y) = \mu(x,y) + \sum_{j:t_j<t} v(t-t_j) \times g(x-x_j; y-y_j; M_j - M_c) \tag{2}$$

where M_c is the cutoff magnitude. Various kinds of $g(\cdot)$ functions are proposed.

Several tests for structural breaks are available in literature (e.g. by Chow, Quandt and Brown, Evans and Rubin). As noted by Hansen (1990), test procedures based on repeated estimation of the model are demanding, and not practically applicable, in case of complex models, which require relevant computational efforts. Therefore the author proposes a Lagrange multiplier (LM) test which only requires to estimate the model under the null hypothesis of no variations in the parameters.

3 Results

The analysis of the data leads to identify two periods when the seismic activity is appreciably intensified: the first between the end of 1997 and the first half of 1998, when the area was partially affected by the earthquake sequence in Umbria and Marche, and the second since April 6th main shock in L'Aquila. These two events clearly represent a departure from the normal seismicity in the area, and shall be excluded from the analysis to avoid conditioning the results. Therefore, we consider the period from June 1st, 1998 and March 31th, 2009.

The first analysis accomplished with the ZIP model confirm the importance of considering the temporal correlation, but they are in contrast with the claim for a change on October 28th 2008 (see Table 1), as stated by Papadopoulos et al., while a change at the end of March 2009 seems to be more reasonable (see Table 2).

	Estimate	Std. Error	z value	$Pr(>\|z\|)$
μ regression				
Intercept	-0.136	0.036	-3.778	0.000
AR(1)	0.106	0.012	8.810	$< 2 \cdot 10^{-16}$
p regression				
Intercept	-0.347	0.072	-4.855	$1.2 \cdot 10^{-6}$
Break date: 2008/10/28	0.136	0.118	1.148	0.251
	$AIC = 8244$	$p = 0.41402$ (SE 0.02457)		

Table 1: ZIP model (1) – no significant break is detectable on October 28th 2008.

	Estimate	Std. Error	z value	$Pr(>\|z\|)$
μ regression				
Intercept	-0.132	0.036	-3.689	0.000
AR(1)	0.088	0.013	6.695	$2.2 \cdot 10^{-11}$
p regression				
Intercept	-0.363	0.073	-4.998	$5.8 \cdot 10^{-7}$
Break date: 2009/03/25	1.133	0.266	4.264	$2.0 \cdot 10^{-5}$
	$AIC = 8220$	$p = 0.41028$ (SE 0.02525)		

Table 2: ZIP model (2) – a significant break occurs on March 25th 2009.

ETAS model analysis is in a preliminary stage, but similar results seem to arise: Figure 1 shows a change in the residual process at the end of the considered period.

4 Concluding remarks

Due to different seismicity patterns empirically observed, the result of the analysis may vary with respect to the location and the extension of the considered area.

With respect to the period and the location we consider, and albeit further investigation is necessary, we shall doubt about a significant change occurred at the end of October 2008, but we can expect it to be identifiable in late March 2009.

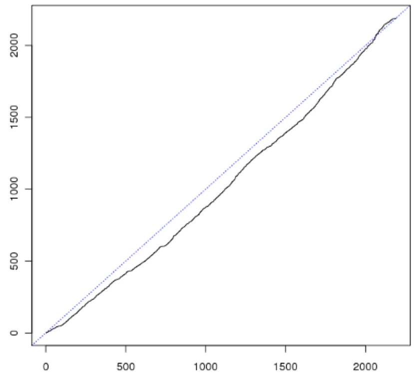

Figure 1: Residuals of the ETAS model

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