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Probabilistic seismic hazard estimation in low-seismicity regions considering non-Poissonian seismic occurrence

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SUMMARY

In low-seismicity regions, such as France or Germany, the estimation of probabilistic seismic hazard must cope with the difficult identification of active faults and with the low amount of seismic data available. Since the probabilistic hazard method was initiated, most studies assume a Poissonian occurrence of earthquakes. Here we propose a method that enables the inclusion of time and space dependences between earthquakes into the probabilistic estimation of hazard. Combining the seismicity model Epidemic Type Aftershocks-Sequence (ETAS) with a Monte Carlo technique, aftershocks are naturally accounted for in the hazard determination. The method is applied to the Pyrenees region in Southern France. The impact on hazard of declustering and of the usual assumption that earthquakes occur according to a Poisson process is quantified, showing that aftershocks contribute on average less than 5 per cent to the probabilistic hazard, with an upper bound around 18 per cent.

Key words: aftershocks, low-seismicity regions, probabilistic hazard, seismic modelling, statistical methods, synthetic-earthquake catalogues.

1 INTRODUCTION

The assessment of probabilistic seismic hazard is required for the establishment of zoning maps over large regions or in the context of seismic risk studies for sites that deserve special attention (e.g. nuclear power plant sites). In low-seismicity regions, such as France or Germany, the estimation of probabilistic seismic hazard must cope with the difficult identification of active faults and with the small amount of seismic data available (very few large-magnitude earthquakes and very little if any strong ground motions recorded). The determination of the probabilistic seismic hazard at a particular site requires the estimation of $P(A \geq A^*$ in $t)$, the probability with which ground motion values of interest (A^*) are expected to be exceeded at least once during a certain time interval of duration t (SSHAC 1997). For example, in the case of conventional buildings, it is a standard practice to base design on those ground-motion levels which have an exceedance probability of 10 per cent over a 50 yr time period (comparable to the lifetime of ordinary buildings). In this context, the hazard analyst has to assume a model for the temporal and spatial occurrence of earthquakes in the region under study. Since the probabilistic method was initiated (Cornell 1968; McGuire 1976), most studies assume a Poissonian occurrence of earthquakes, that is, a random occurrence in time and space. However, it is now well-known that the recurrence of earthquakes is characterized by long-term and short-term patterns (Scholz 1990). In seismically highly active regions where active faults have been identified and their characteristic is well known, long-term behaviour (seismic cycles) can be taken into account. In these special cases, time-dependent models such as renewal models have been implemented in probabilistic hazard studies (e.g. Cornell & Winterstein 1988). In low-seismicity regions, it is extremely difficult to introduce long-term behaviour because active faults cannot be identified in most cases; thus the Poisson process is more or less exclusively used. However, short-term behaviour characterized by aftershocks occurrence can be addressed.

Here we propose a method that enables the inclusion of spatio-temporal earthquake clustering into the hazard calculations. For this purpose, we combine the statistical seismicity model Epidemic Type Aftershocks-Sequence (ETAS; Ogata 1988) with a Monte Carlo technique. This method is applied to the Pyrenees area, a low-seismicity region in Southern France. Furthermore, the impact of declustering and of the Poissonian assumption on hazard is quantified.

2 PROBABILISTIC METHODOLOGY

Within the standard probabilistic methodology (Cornell 1968; McGuire 1976; Reiter 1990), the hazard at a site is computed by taking into account the contributions from all potentially damaging earthquakes in the region. In low-seismicity areas, a Poisson process is usually assumed. As a consequence, since occurrences of earthquakes are fully described by their annual rates, the seismic hazard [$P(A \geq A^*$ in $t)$] can be computed in terms of annual rates of exceedance of selected spectral acceleration levels at the site of interest (see eq. 3). To establish the set of earthquakes to take into

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account, seismic sources are identified and classified according to various criteria (geological, geophysical or seismological). For an areal source zone, the Gutenberg–Richter model is usually used to provide a probability density function for magnitude occurrences. The corresponding model parameters (*a*- and *b*-values) are derived from the available seismic catalogues previously declustered. The set of source-site distances is obtained by subdividing the source zones into smaller units. Finally, a ground motion model is required to compute for each earthquake its probability of producing a ground-motion higher than the acceleration level considered at the site. For an earthquake *i* of magnitude M_i at source-site distance R_i with annual rate of occurrence λ_i, the annual rate of exceedance of a target acceleration level A^* at the site is

$$\lambda_i^e = \lambda_i P\left(A \geq A^* \mid M_i, R_i\right) \tag{1}$$

with $P(A \geq A^* \mid M_i, R_i)$ being the probability that this event produces an acceleration level at the site of interest higher than A^*. The annual exceedance rate at the site is then obtained by summing the contributions from all events to be considered:

$$\lambda_{A^*}^e = \sum_i \lambda_i^e. \tag{2}$$

The spectral acceleration corresponding to a particular rate of interest can be obtained by interpolation. Finally, for a Poissonian process, $P(A \geq A^*$ in $t)$ can be calculated from the annual rate of interest λ by the following formula (Ang & Tang 1975):

$$P = 1 - e^{-\lambda t}. \tag{3}$$

For example, a probability of 10 per cent over 50 yr corresponds to an annual rate of exceedance of 0.0021, or its reciprocal the average return period of 475 yr. For small values of λt, the series expansion of the right-hand side of eq. (3) can be truncated after the first term, and the exceedance probability becomes approximately equal to the annual rate λ times *t*, or in other words to *t* divided by the average return period.

Instead of summing earthquake contributions, several recent studies computed probabilistic hazard by generating synthetic seismicity catalogues based on a Monte Carlo technique (e.g. Musson 1998, 1999a, 2000; Park & Hashash 2005). The magnitudes, times and locations of earthquakes are usually generated using the particular probability density functions derived for each source zone. Dealing with Poissonian seismicity, either a very long or numerous short catalogues are generated. The annual rate of exceeding a given ground motion is obtained by counting all instances of ground motion reaching or exceeding the given threshold and dividing by the length of the long catalogue (Smith 2003). Alternatively, the annual exceedance probabilities can be obtained by sorting annual ground motion maxima at the site (Musson 2004). In terms of resulting hazard, these Monte Carlo techniques are equivalent to the classical probabilistic method, provided that the same seismicity model is used and that the total number of years for which the catalogues are generated is sufficiently large (Musson 1998). Some studies use synthetic catalogues as a convenient way of taking into account uncertainties (e.g. Musson 1999b; Smith 2003; Giardini *et al.* 2004). Most authors also stress that it permits an easy integration of hazard studies inside risk studies, due to the clear identification of seismic scenarios. On the other hand, Ebel & Kafka (1999) generate synthetic earthquake catalogue by sampling with replacement a real earthquake catalogue. All these previously studies used Poissonian synthetic earthquake catalogues.

When a non-Poissonian model is assumed, eq. (3) does not hold anymore and the hazard cannot be expressed in terms of return periods any longer. The difference with the previous-cited studies is that when generating synthetic seismic catalogues, ground-motion maxima must be selected in time intervals with length the period of interest. Here we propose to compute probabilistic seismic hazard including short-term clustering by taking advantage of the statistical seismicity model ETAS (Ogata 1988) to generate synthetic catalogues. For the determination of hazard, we generate a certain number (N) of catalogues for durations of *t* years each (e.g. 50 yr). Each catalogue is considered as a possible realization of the seismicity over a particular time interval. For each catalogue, the set of ground motions occurring at the site during the time period *t* is determined. In the limit for large N, the probability of non-exceedance of the level A^* over *t* years is obtained by counting those intervals in which A^* has not been exceeded:

$$P(A^*, t) = \lim_{N\to\infty} \frac{1}{N} \sum_{i=1}^{N} H\left(A^* - A_{\max,i}(t)\right). \tag{4}$$

Here, N is the number of time periods of length *t*, $A_{\max,i}$ is the maximum ground motion occurring at the site during the *i*th *t* year period, and H is the Heavyside function. The complement of $P(A^*, t)$ is then the probability that A^* is exceeded at least once in the time period *t*. It is equivalent and faster to consider the distribution of maximum accelerations $A_{\max,i}$ and to deduce directly from this distribution the probabilities of non-exceedance of acceleration levels (corresponding to the percentiles). Any probability of non-exceedance over the time period of interest can thus be deduced. However, the higher the probability of non-exceedance is, the larger the number of catalogues has to be in order to get a stable result. To demonstrate that, in the case of the Poisson hypothesis, this method yields exactly the same hazard estimate as the Monte Carlo approach summing exceedances over one long seismic catalogue (as used by e.g. Smith 2003); both methods are applied on one long synthetic example catalogue. Fig. 1(a) displays annual rates versus spectral accelerations calculated from a 50 000-yr Poissonian catalogue at an example site. Using eq. (3), the hazard is also displayed in terms of probabilities of non-exceedance over 50 yr (Fig. 1b). The distribution of the maximum accelerations in the 1000 subcatalogues of 50 yr durations is displayed in Fig. 1(c), and the accelerations corresponding to five selected percentiles of this distribution (or probabilities of non-exceedance) are highlighted (solid squares). For visual comparison, these couples (acceleration, probability) are superimposed on Figs 1(a) and (b).

3 THE STATISTICAL SEISMICITY MODEL

3.1 Definition

The seismicity model ETAS is a stochastic point process model which was introduced by Ogata (1988) and further developed by several authors (e.g. Felzer *et al.* 2002; Helmstetter & Sornette 2002). In a point process model, earthquakes are considered to be events characterized only by an occurrence time, location, and magnitude. In the ETAS model, an event can be both an aftershock of a preceding large event and a mainshock of a following earthquake. Earthquake occurrences are modelled as cascades: the Poissonian earthquakes produced by the tectonic loading of the area trigger the first generation of aftershocks; these aftershocks produce their own aftershocks and so on. The triggered events can have a higher magnitude than their mainshocks. The model relies on the following.

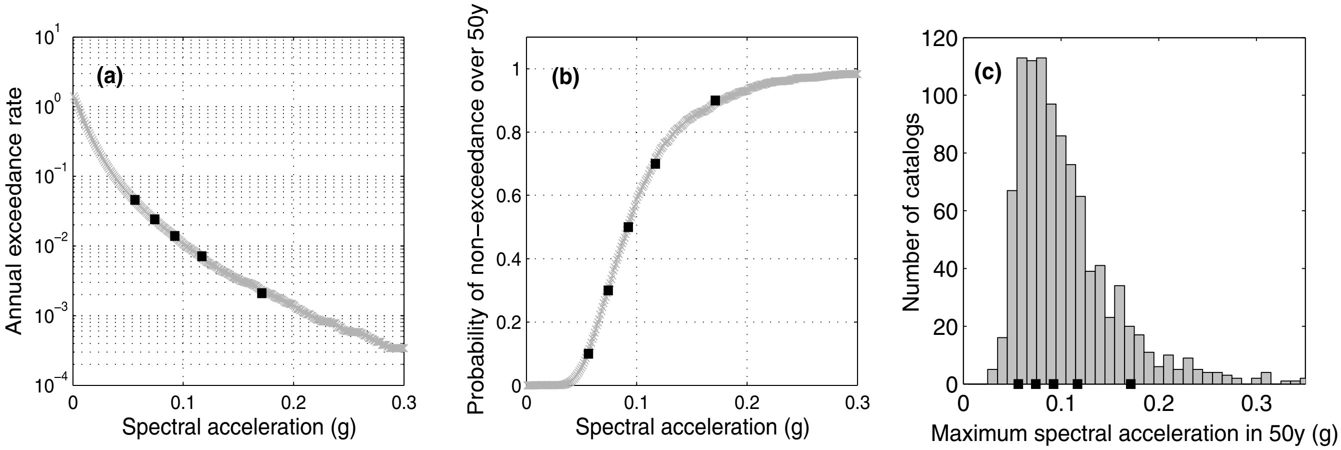

Figure 1. Computation of probabilistic hazard at one site from Poissonian catalogues. Hazard curves (grey crosses): (a) annual rates of exceedance calculated for a 50 000-yr catalogue and (b) corresponding non-probabilities of exceedance over 50 yr using eq. (3). (c) Distribution of maximum acceleration observed in the 1000 subcatalogues of 50 yr, yielding compatible results with the hazard curves: acceleration levels corresponding to probabilities of non-exceedance of 10, 30, 50, 70 and 90 per cent are highlighted (solid squares). For visual check, these couples (acceleration, probability) are superimposed on the hazard curves of (a) and (b).

(i) The background seismicity, modelled as a stationary Poisson process with a constant occurrence rate μ.

(ii) The modified Omori law (Utsu *et al.* 1995) for the description of the decrease of the aftershock rate with time after a mainshock: the number of aftershocks is proportional to $(t + c)^{-p}$, with t the time from the occurrence of the mainshock.

(iii) An estimation of the number of aftershocks generated by an earthquake scaled with magnitude M. The number is proportional to $K10^{\alpha M}$, with the same α for all earthquakes and K depending on the minimum magnitude considered.

(iv) A frequency–magnitude distribution for the selection of magnitudes. Usually the Gutenberg–Richter distribution truncated at a maximum magnitude is used. The same distribution is assumed for tectonic events and triggered events.

3.2 Inversion of parameters for the considered region

We focus on an area of 250 × 500 km in the South of France, delimited by the window (−2° to 4°) in longitude and (42° to 44°) in latitude (Fig. 2). We use the instrumental catalogue provided by the Laboratoire de Détection et de Géophysique (Nicolas *et al.* 1998) containing homogeneous local magnitudes M_L and covering 38 yr (1962–99). The joint inversion of the required parameters (μ, K, α, p, and c) requires a large number of earthquakes to yield reliable estimates. Therefore, we decided to fix α, p and c to frequently found values and to invert only μ and K using the maximum-likelihood method (Ogata 1993). Following Helmstetter (2003), α is fixed to 0.8. In addition, we use c = 0.0194 days (Console & Murru 2001) and $p = 1.1$ (Ogata 1998). The parameters c and p control the distribution in time of the aftershocks; the precision on their estimation is not crucial considering the time length of the simulated seismic catalogues (50 yr) and the range of magnitudes occurring in the region. Using all magnitudes above 3.0 over the period (1980–1999), the inversion yields $\mu = 16$ yr^{-1} and $K = 0.0082$. Note that based on the Akaike's Information Criterion (Akaike 1974) to compare the goodness-of-fit, we checked that the seismicity is significantly better described by the ETAS model than by the Poisson model. Furthermore, the b-value estimated from the catalogue of the whole region is close to 1.0. The highest magnitudes in the historical catalogue SisFrance (http://www.sisfrance.net/), estimated using the Levret *et al.* (1994) intensity–magnitude correlation, are between 6.0 and 6.5; the maximum magnitude is fixed to 6.5.

3.3 Generation of synthetic seismic catalogues

First, the tectonic earthquakes are distributed in space according to a probability density map determined from past earthquakes. This background seismicity density grid (Fig. 2) is calculated from the declustered instrumental catalogue of the whole seismic zone, after declustering with Reasenberg's algorithm (Reasenberg 1985), which removed approximately 25 per cent of the events, and considering only earthquakes with magnitudes equal or higher than M3.0. The declustering algorithm uses a circular space – time window depending on the magnitude of the mainshock. We selected 20 days as the maximum look-ahead time for clustered events and 10 km as the interaction radius of dependent events. Errors on the location of earthquakes are taken into account. Cells of 0.1° × 0.1° are used to compute the cumulated seismic rates and a Gaussian smoothing is performed (with a distance correlation of 20 km). The clustered events are then distributed in the vicinity of their 'mainshock', according to an isotropic power-law distribution (eq. 16 in Helmstetter *et al.* 2003). Note that we find that our results are almost independent of the choice of this spatial probability distribution for clustered events. Moreover, since uncertainty on the depth estimation is known to be high, for simplicity all earthquakes are attributed a depth of 10 km (mean depth for earthquakes in France, Autran *et al.* 1998).

4 HAZARD ESTIMATION AT TWO EXAMPLE SITES

The time interval considered here is 50 yr and 20 000 catalogues are generated. This number of synthetic catalogues has turned out to be sufficient to get a stable distribution. The minimum magnitude of events is fixed to 3.0 so that low magnitudes can contribute to the cascade process. For each earthquake, the acceleration produced at the site is selected in the Gaussian density distribution predicted

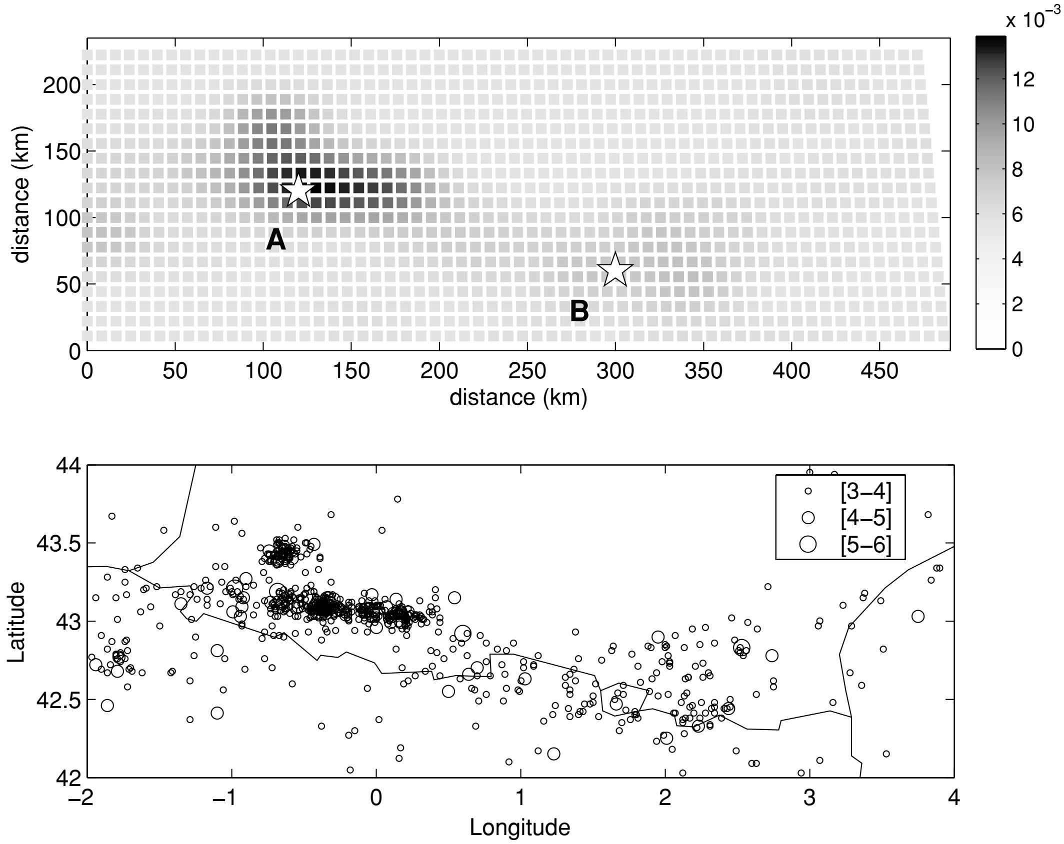

Figure 2. Probability density map determined from the declustered instrumental catalogue (M3.0+, 1980–99), cells of 0.1° × 0.1°, Gaussian smoothing with a 20 km correlation distance. Stars: two sites considered in this study. Seismicity map displaying the declustered instrumental catalogue (1962–99).

by the ground-motion model used. We use here the Berge-Thierry *et al.* (2003) attenuation relation characterized by a standard deviation of 0.2923 (log10, Peak Ground Acceleration) reflecting the natural aleatory variability of ground motions. The acceleration corresponding to any probability of non-exceedance over 50 yr can then be deduced from the distribution of maximum accelerations.

Regarding the prediction of ground motions, similar decisions as in any probabilistic study must be taken: in order not to get unrealistic high values of ground motions at the very small probabilities of exceedance (high percentiles); the Gaussian function representing the aleatory variability of ground motions is truncated. The truncation used here is three standard deviations above the mean of the logarithm of spectral acceleration. The choice of the truncation is rather arbitrary and will remain so until physical upper bounds on ground motions can be determined (Bommer *et al.* 2004). Moreover, only the earthquakes with magnitude higher than 4.0 are taken into account in the probabilistic computations, in order to prevent the lower magnitudes with high probabilities of occurrence but very low probabilities of producing significant ground motions to participate extensively to the hazard (see, e.g. Beauval & Scotti 2004). Note that the impact on hazard of the Poisson hypothesis as quantified in Section 5 is not dependent on these choices; our tests show that the impact estimates are stable using a truncation at two standard deviations or using a higher/lower minimum magnitude.

Probabilistic hazard estimates are computed for two sites, one is representative of a moderate-seismicity zone and located in the Western Pyrenees (site A, Fig. 2) and other is representative of a low-seismicity zone and located in the Eastern Pyrenees (site B). The probability density functions for the maximum spectral acceleration in 50 yr are displayed in Fig. 3. For example, spectral acceleration values of 0.3 g (A) and 0.18 g (B) are obtained for a 90 per cent probability of non-exceedance over 50 yr; whereas, 0.18 g (A) and 0.09 g (B) are obtained for a 50 per cent probability.

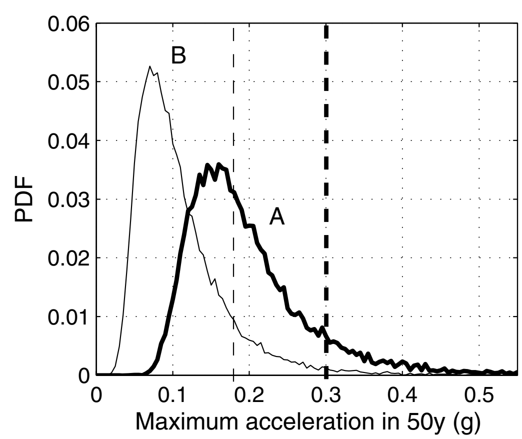

Figure 3. Probability Density Function of maximum acceleration in 50-yr catalogues (Peak Ground Acceleration), for the point A (thick curve) and the point B (thin curve), based on 20 000 catalogues. Dashed lines indicate 90 per cent percentile of distribution, yielding 0.3 g at location A and 0.18 g at location B.

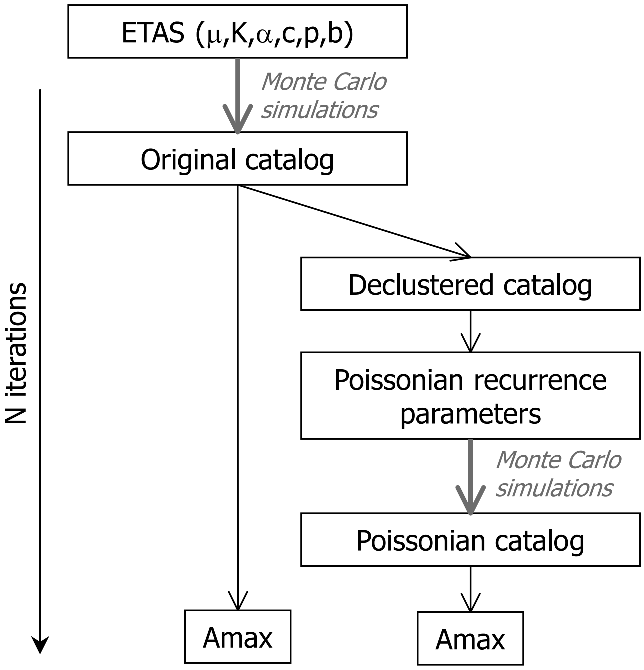

Figure 4. Scheme of the procedure followed for quantifying the impact of the usual assumptions that earthquakes occur according to a Poisson process in time and space on hazard estimates (see text).

5 QUANTIFICATION OF THE IMPACT ON HAZARD OF THE POISSON HYPOTHESIS

5.1 Objective and methodology

In all probabilistic studies assuming a Poissonian occurrence for earthquakes, the seismic catalogue is declustered, in order to fulfil the Poissonian hypothesis. Different methodologies are used for identifying aftershocks, from simple windows in time and space to more complex algorithms. We study the impact of the declustering and of the usual assumption that earthquake occurrences are Poissonian on hazard (see scheme, Fig. 4). The distribution of maximum accelerations in t years is computed as described previously, by generating N catalogues of length t years. In parallel, at each iteration, aftershocks are identified using a declustering algorithm that has become quite standard in probabilistic studies (Reasenberg 1985) and the recurrence parameters are estimated on the declustered catalogues. Based on these parameters, a new Poissonian catalogue is generated. Earthquakes are distributed in space according to the density probability grid, yielding another estimation of hazard.

5.2 Results

The same two example sites are considered. The impact of the Poisson hypothesis is quantified by computing for each percentile the normalized difference between the original and the Poissonian acceleration estimates (solid lines in Fig. 5). The impact on hazard is low and comparable at both locations: the decrease of hazard values is lower than 5 per cent. For high accelerations (high percentiles), the impact is close to zero. Although aftershocks concern low magnitudes and thus a small fraction of the total seismic moment, it was not expected to get such a low impact after removing between 15 and 35 per cent of events from the seismicity catalogue (Fig. 6a). Looking at the recurrence parameter values estimated before and after the declustering, however, suggests a simple explanation: not only the seismic rates (Fig. 6b), but also the b-values (Fig. 6c) are decreasing, thus potentially increasing the rates of magnitudes higher than a crossing magnitude (Fig. 7a). As shown in Fig. 7(b), this crossing magnitude can occur between M4.5 and $M_{\max} = 6.5$, depending on the catalogue. The b-values decrease because—due to the way of identifying aftershocks in the declustering algorithm—there are proportionally more low-magnitude events removed than high-magnitude events. The crossing occurs because the maximum magnitude is attributed independently from the computation of the recurrence parameters. The time interval considered is short in comparison with the recurrence rates of the highest magnitudes, implying that the maximum magnitudes of synthetic catalogues can be lower than the maximum magnitude $M_{\max}$ bounding the Gutenberg–Richter recurrence curve (Fig. 7c). This effect can affect any probabilistic hazard estimation requiring the modelling of the recurrence curves on a limited data set and estimating the

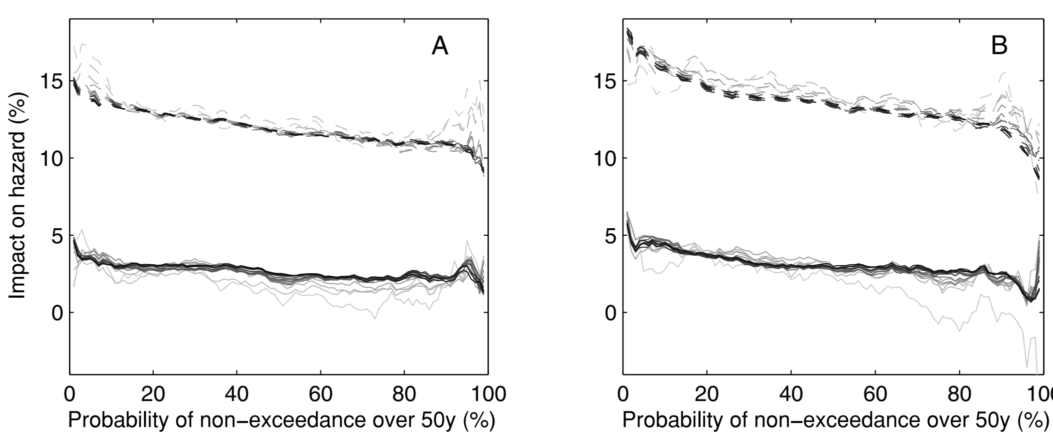

Figure 5. Impact of the declustering and the assumption that earthquake occurrences are Poissonian on hazard estimates at two locations. The impact for each percentile is defined as the normalized difference between the acceleration computed from the original catalogues and the acceleration computed from the Poissonian ones (see Fig. 4). Solid lines: the darker the colour, the more numerous the number of catalogues used, from 5000 catalogues to 80 000 with a 5000 step; a minimum number of 20 000 is required for a stable estimation. Also shown is the impact of not taking into account clustered events as defined within the ETAS model (dashed lines), yielding an upper bound to the impact of declustering.

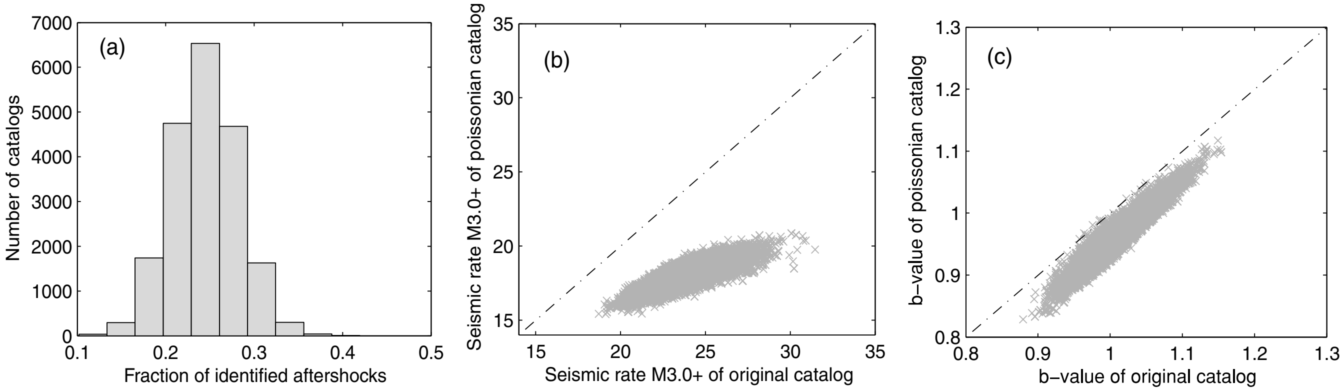

Figure 6. (a) Fraction of clustered events identified as aftershocks with the declustering algorithm. Effect of the declustering of catalogues on recurrence parameters: seismic rates M3.0+ (b) and *b*-values (c) decrease, potentially increasing the seismic rates for magnitudes higher than a crossover magnitude (Fig. 7a).

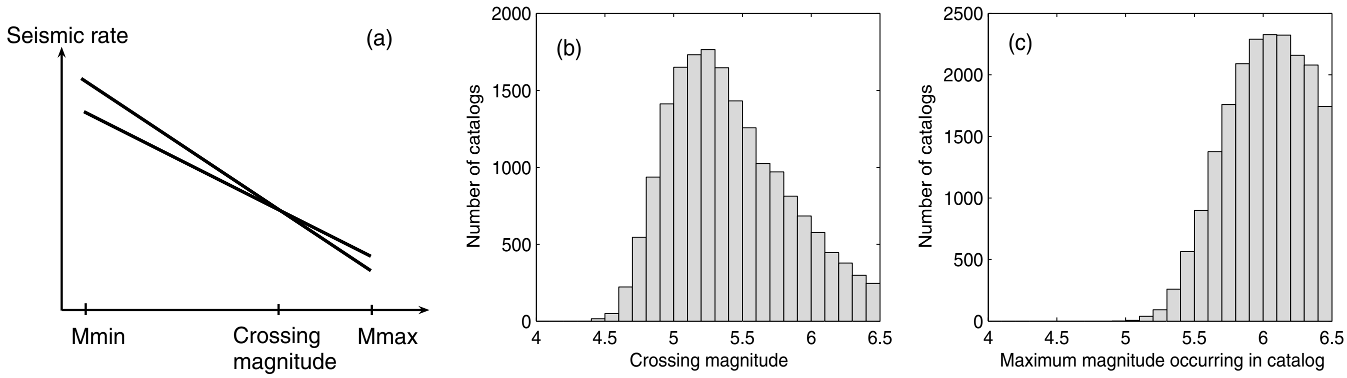

Figure 7. (a) Gutenberg–Richter curves before and after applying the declustering algorithm: increase of seismic rates for magnitudes above a crossing magnitude. (b) Distribution of crossing magnitudes and (c) distribution of maximum magnitudes of synthetic catalogues.

maximum magnitude independently, from historical or geological data.

5.3 Upper bound for the impact of the Poisson hypothesis on hazard

In the philosophy of ETAS, seismicity does not consist of mainshocks and aftershocks but of Poissonian background events and triggered ones. Computing the hazard only on the background events of each catalogue provides lower hazard estimates than the results of the previous test (dashed lines in Fig. 5); the decrease on hazard reaches 18 per cent for lowest probabilities of non-exceedance. Several reasons contribute to this effect. First, the declustering algorithm seems not to identify all dependent events, the fraction of aftershocks identified is lower than the real fraction (Fig. 8). Furthermore, in the ETAS model, the triggered events can occasionally have a higher magnitude than their 'mainshock'; whereas, by declustering the catalogue with the Reasenberg algorithm, the highest magnitudes in clusters are always processed as mainshocks and kept. Thus, the *b*-values remain stable after removing clustered events and in this case, the decrease of the hazard level is due to the decrease of the seismic rate for all magnitudes. The decrease of hazard is slightly higher in the low-seismicity region (point B) than in the moderate one (point A). This test provides with an upper bound for the impact on hazard of the Poisson hypothesis.

It is worth noting that we performed the same tests with arbitrarily modified ETAS parameters, for example, with μ divided by 2 and K multiplied by 3, thus increasing the fraction of clustered events. The results show that the impact of the Poisson hypothesis as quantified in Section 5.2 (applying a declustering algorithm) remains lower than 5 per cent. On the other hand, the upper bound estimated from the ETAS background events increases with the fraction of clustered events.

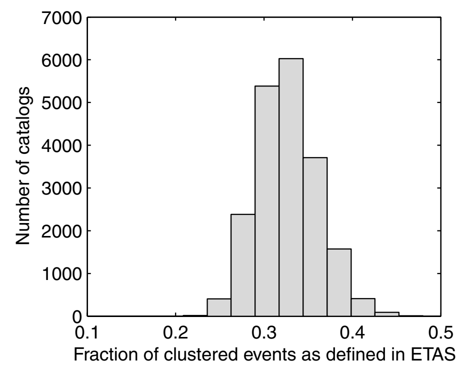

Figure 8. Fraction of clustered events as defined in ETAS model.

5.4 Disaggregations

The behaviour of the Gutenberg–Richter parameters is useful for understanding the observed impacts. However, because of the necessity to use ground motion models for predicting ground

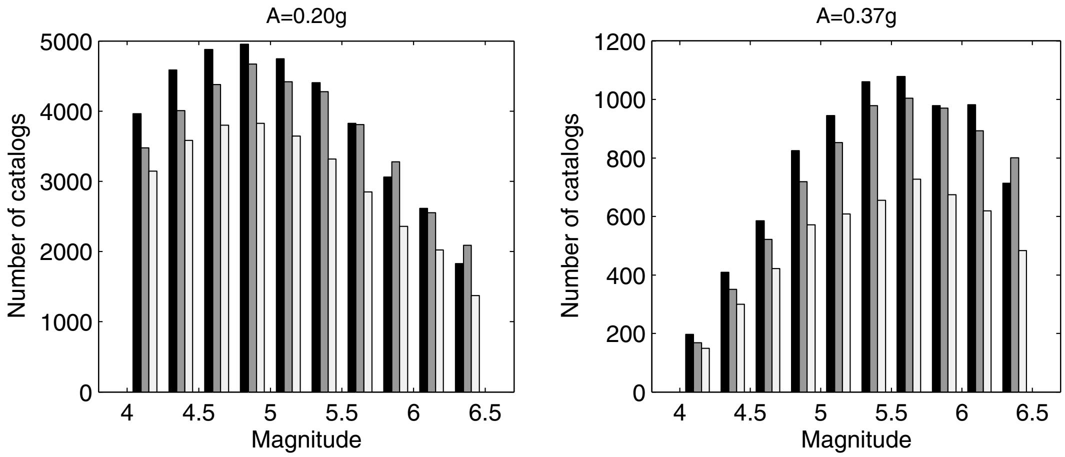

Figure 9. Disaggregations in magnitude for two levels of acceleration at site A (0.2 g and 0.37 g), for hazard estimations based on three different seismic catalogues. Black: original catalogues; grey: catalogues declustered with Reasenberg's algorithm; white: catalogues containing only independent events (background seismicity in ETAS model).

motions at the site, only disaggreggation studies provide the full amount of contributions to hazard per magnitude. The disaggregation, that is, the estimation of the contributions to hazard according to magnitude and distance (Bazzurro & Cornell 1999), is straightforward as the seismicity scenarios are clearly identified in the Monte Carlo process (Musson 1999a, 2004). For clarity, we compare magnitude disaggregation for a fixed acceleration level, for hazard computed (i) from the original catalogues, (ii) from declustered and spatially redistributed catalogues (Section 5.2), and (iii) from the events defined as non-clustered seismicity in the original catalogues (Section 5.3). Two acceleration levels are considered (Fig. 9). As expected, when the acceleration increases, the barycentre of the magnitude contributions shifts towards high magnitudes. For both acceleration levels considered, the compensating effect is observed, with higher contributions above magnitude 5.5 for estimates based on declustered catalogues than for estimates based on original catalogues. On the other hand, for the whole range of magnitudes, the contributions based on non-clustered events are always lower than the contributions based on the original catalogues.

5.5 Quantifying the impact using a new technique for estimating aftershock fraction

Recently, a new method for estimating the fraction of dependent events in a seismic catalogue proved to be more efficient than classical declustering algorithms such as Reasenberg's. Based on the results of Corral (2004) and Molchan (2004), Hainzl *et al.* (in press) showed that the fraction of aftershocks can be retrieved from fitting the normalized interevent time distribution by a gamma function. Using this new technique in the procedure described in Section 5.1 yields another estimation for the impact of assuming the Poisson hypothesis on hazard (Fig. 10). For both sites, impacts take values between 0 and 14 per cent, depending on the probability of exceedance considered. The impact is higher than when using Reasenberg's algorithm and lower than when retrieving clustered events as defined in ETAS model, which is expected as more earthquakes are identified as aftershocks and retrieving all clustered events yields an upper bound for any meaningful declustering method.

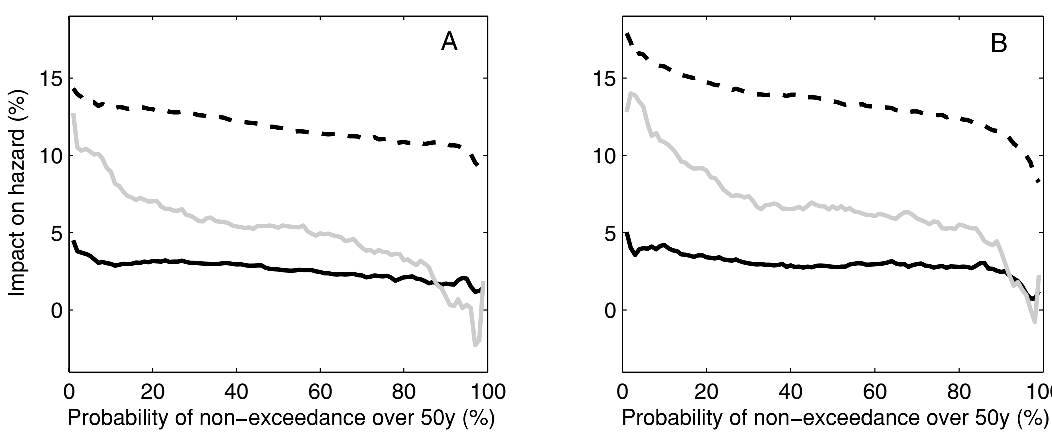

Figure 10. Impact of the declustering and of the assumption that earthquake occurrences are Poissonian on hazard estimates at two locations. Estimates based on the method by Hainzl *et al.* (grey line) are superimposed to the upper-bound estimates (dashed line) and to the estimates obtained using Reasenberg's algorithm (solid line).

6 CONCLUSIONS

We introduce a method to compute probabilistic seismic hazard for low-seismicity regions which takes into account temporal and spatial dependencies between earthquakes. Its two constituents are a statistical seismicity model (ETAS) and a Monte Carlo technique. Even in cases where it is not possible to identify individual faults and introduce long-term time-dependent models, the Poisson hypothesis can be abandoned for more realistic seismicity models. Using the ETAS model, aftershocks can easily be taken into account in the probabilistic hazard estimation. We take advantage of this method to study the impact of the declustering and the usual assumption that earthquakes occur according to a Poisson process on the hazard estimation. The results for the test region in the Pyrenees show that the aftershocks identified by a standard declustering algorithm contribute less than 5 per cent to the probabilistic hazard, with 20 to 30 per cent of events in the catalogues identified as aftershocks and for sites located in moderate- and low-seismicity zones. Based on the definition of background events in the ETAS model, an upper bound of 18 per cent is obtained as impact of neglecting clustering on hazard. Other steps and decisions required by the probabilistic hazard methodology are known to bring even higher uncertainties to hazard estimation; up to now there is no consensus on the identification of aftershocks in a seismic catalogue; keeping all earthquakes might introduce less uncertainties than declustering the catalogue. The methodology presented here is applicable to other spatio-temporal variations of seismicity as well, which is the topic of ongoing research.

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