A spatially smoothed seismicity forecasting model for $M_W \geq 5.0$ earthquakes in northern Algeria and Morocco

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SUMMARY
We study the correlation between locations of $M_W \geq 5.0$ earthquakes and locations of $5.0 > M_W \geq 4.0$ events for Northern Algeria and Morocco. A preliminary study shows that it can be observed a relatively good agreement between locations for these two data sets, that is, minor earthquake locations could be used to forecast future places where will happen moderate to strong earthquakes.
Then, we propose a time-independent forecasting model based on the spatially smoothed seismicity rate of $M_W \geq$ 4.0 earthquakes. Initially, the area under study was divided into square cells. The number of earthquakes with magnitude $M_W \geq 4.0$ that have taken place at a given cell is counted and smoothed.
The time-independent forecasting model is proposed from the computation of $M_W \geq 5.0$ earthquake probabilities for each cell for different exposure times. Probabilities are computed considering that seismicity follows both a Poisson process and the Gutenberg-Richter magnitude-frequency relationship.

Keywords: Spatially smoothed seismicity, seismic forecast models, Northern Algeria, Northern Morocco

1. INTRODUCTION

The approach proposed by Frankel (1995) in order to compute seismic hazard values has been widely used in the last years, being that used nowadays, for example, to compute the USGS National Seismic Hazard Maps. This method models the seismicity that cannot be assigned to specific geological structures, termed as distributed or background seismicity. In this type of studies, the region is divided into square cells, and the number of earthquakes above a certain reference magnitude is counted. This count, that is, the total number of events observed above the threshold magnitude is the maximum likelihood estimate of the *a*-parameter in the Gutenberg-Richter relationship (Weichert, 1980). Then, it is smoothed spatially, thus, including the uncertainty in the earthquake location in the final seismic hazard results. To perform the smooth, it is usual to use a Gaussian filter because it preserves the total number of earthquakes. Finally, the computation is based in the well-known total probability theorem, expressed in terms of rate of exceedance of a certain level of ground motion.

Using this approach, our research group has carried out seismic hazard assessments, among other places, in Portugal and Spain (Peláez and López Casado, 2002) and Algeria (Peláez *et al*., 2003). Afterwards, these assessments have been updated and extended not only to peak ground horizontal acceleration (PGA) values but to spectral acceleration (SA), uniform hazard spectra (UHS) and even Arias intensity (AI) values (Peláez *et al*., 2005a, 2005b, 2006; Hamdache *et al*., 2012).

Among other sources of uncertainty in probabilistic seismic hazard studies, we must consider the characterization of seismic sources, and specially, the ground-motion attenuation models (SSHAC, 1997). In this work we present a preliminary time-independent forecasting model, the first component of any seismic hazard assessment, dodging the second one, the issue of the estimation of the ground-motion level. Thereby, the final results obtained in the assessment do not include the typical epistemic and aleatory (or modelling and parametric ones) uncertainties in ground-motion predictions. To develop this model, we will use a procedure similar to the one used in the spatially smoothed seismicity approach to compute seismic hazard values: each square cell in the study area is assumed to be a source. Our contribution is in the same line of the forecast conducted for the Italian territory by Akinci (2010). This simple study/analysis does not consider explicitly neither the geology (including geophysical, paleoseismic or geodetic studies) of the region nor physical models concerning processes associated with earthquake triggering.

Initially, we will test in our region if minor earthquake locations could be used to forecast future places where will happen moderate to strong earthquakes, which is the main assumption in this type of studies (Frankel, 1995). The authors of this work do not agree with a uniform background zone used as an applicable model in seismic hazard or forecasting studies (Peláez and López Casado, 2002; Peláez *et al*., 2003), that is, to assume that certain type of events can occur anywhere with equal probability. In any case, this assumption will be also checked.

2. BRIEF REGIONAL SETTING

The Maghrebian region (Fig. 1) occupies the NW part of the African (Nubia) Plate in what is referred to its continental crust. Its oceanic crust continues till the area of the Azores Islands. To the N it is immediately situated the Eurasian Plate, although between the Gibraltar Arc and the S of Italy an intermediate complex domain is intercalated. This domain is formed by some oceanic basins, as is the Algero-Provençal Basin and the Thyrrehnian Basin, and by a former region, presently disintegrated and now forming the Betic-Rifean Internal Zone, the Kabylias (in Algeria), the Peloritani Mountains (Sicily) and the Calabrian area in Italy (AlKaPeCa domain). This area underwent from the early Miocene a northwards subduction of Africa, then opening the small oceanic basins quoted, accompanied by the disintegration of the AlKaPeCa domain.

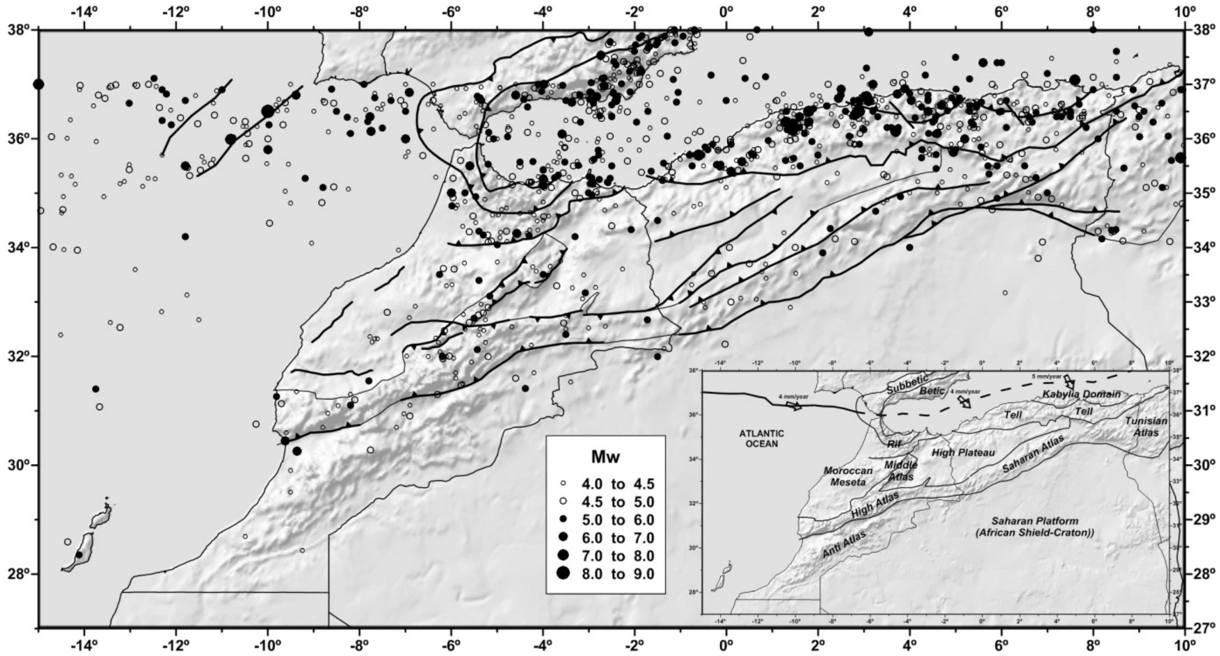

Fig. 1. Tectonic sketch showing the main tectonic domains and used seismicity (see text).

Presently, the convergence between the Nubia Plate and Iberia has an approximate NNW-SSE direction, with values of the order of 3 to 5 cm/year, according the places. This compression is accompanied, at least in the area of the Gibraltar Arc (in the Alboran Sea) by a noticeable ENE-WSW tension, in some cases even more important than the compression. For this reason, in the Alboran area, some extensional movements can be important.

The Maghrebian region is also a complex area in which the Saharan Shield affected by the Pan-African Orogeny (Precambrian to early Cambrian) is in contact with the Atlasic Mountains of mainly Alpine age (Fig. 1). To the N of the Atlas is situated the Moroccan Meseta, to the W, and the High Plateaus in Algeria, which to the N contact with the Rif and Tell mountains, typically Alpine chains.

The Saharan Shield forms part of the Precambrian areas of Africa, clearly cratonized and generally not affected by later important deformations. In fact, in the Maghrebian area it corresponds to a clearly stable area. In Morocco, the so called Antiatlas, corresponds to a Precambrian and, mainly, Paleozoic area, making a tectonic transition between the shield and the Atlas.

The Atlasic Mountains correspond to an intracontinental chain. To the W, in Morocco, the High Atlas reach the coast in the Agadir area and continues to the NE and E, passing, although with lesser heights, to the Saharan Atlas, which cross Algeria and reach the central part of Tunis. They can be considered as aulacogens bordering the northern part of the Saharan shield. To the N, the Middle Atlas in Morocco has a different direction, NE-SW, separating the Moroccan Meseta and the High Plateaus, both forming by Paleozoic rocks, although with a Mesozoic and Tertiary cover, well developed in some areas. On the whole, the Atlasic Mountains has been tectonically unstable from the Triassic times, and along the Alpine orogeny suffered important deformations and, more recently, also important volcanism, reaching the Quaternary.

The Rif and Tell thrust southwards the Moroccan Meseta and the High Plateaus, and even in some places part of the Atlasic Mountains. They are formed by sedimentary External zones (only slightly affected by metamorphism in some Moroccan places) and by Internal zones. Mostly Internal zones (divided in several tectonic complexes) are affected by alpine metamorphism, moreover the existence of previous Paleozoic and even older deformations. In any case, their present structure has being formed during the Alpine Orogeny. They appear mainly to the E of Tetuan, in Morocco, and in the Kabylias, in Algeria.

These Alpine chains have being structured from the Cretaceous to the Oligocene-early Miocene. Later, were formed numerous Neogene basins, clearly cutting in many cases previous structures. In this time, particularly from the late Miocene to the present, a near N-S compression provoked the existence of strike-slip faults (NE-SW, sinistral, and NW-SE, dextral), moreover reverse fault, many of which has N70ºE to E-W direction. In many cases, the cited strike-slip faults moved mainly as normal faults, releasing by this way the regional tension, practically perpendicular to the compression.

3. USED CATALOG AND SPATIAL DISTRIBUTION OF EARTHQUAKES

To know if small earthquakes delimit the areas where large earthquakes will happens, as was quoted previously, is the basis of the spatially smoothed approach both in seismic hazard and in this type of forecasting studies. Here we check both spatial distributions in order to confirm or not this hypothesis in our region. Kafka and Ebel (2001) consider that this is the 'least-astonishing null hypothesis', being a standard of comparison for other more complex spatial forecast methods (*v.g.* Zechar and Jordan, 2010; Falcone *et al.*, 2010). These authors call this method cellular seismology.

The reliability of this analysis is related to the reliability of the used catalog, that is, with its completeness and homogeneity. To develop our study, we have used two unified catalogs in terms of moment magnitude, including only main events, compiled specifically for future seismic hazard and forecasting studies in the region, one of them covering Northern Morocco (Peláez *et al.*, 2007) and the second one Northern Algeria (Hamdache *et al.*, 2010). Catalog for Northern Morocco includes earthquakes in the area between 27º to 37ºN and 15ºW to 1ºE. Initially, it spans the years 1045 to 2005. Catalog for Northern Algeria covers the area between 32º to 38ºN and 3ºW to 10ºE, spanning the years 856 to 2008. These catalogs have been updated to June 2011 and aggregated, erasing duplicated earthquakes in the overlapped areas and non-crustal events (events with depth below 30 km) (Fig. 1).

Overall, the final catalog can be considered complete above magnitude M_W 5.0 since 1900, with a mean rate of 2.15 events/year, and above magnitude M_W 6.0 since 1885, with a mean rate of 0.21 events/year. Earthquakes above M_W 4.0 are completes only in the last eight years, that is, since 2003, with a mean rate of 29.82 events by year; in the preceding period 1925-2003, the mean rate is only 7.71 events/year (Fig. 2). We must take into account that Moroccan and Algerian seismological networks have not covered efficiently this region, and mostly earthquakes included in both catalogs are those located by the Spanish National Geographic Institute network, distant of the southern and eastern parts of the study region (Peláez *et al*., 2007; Hamdache *et al*., 2010).

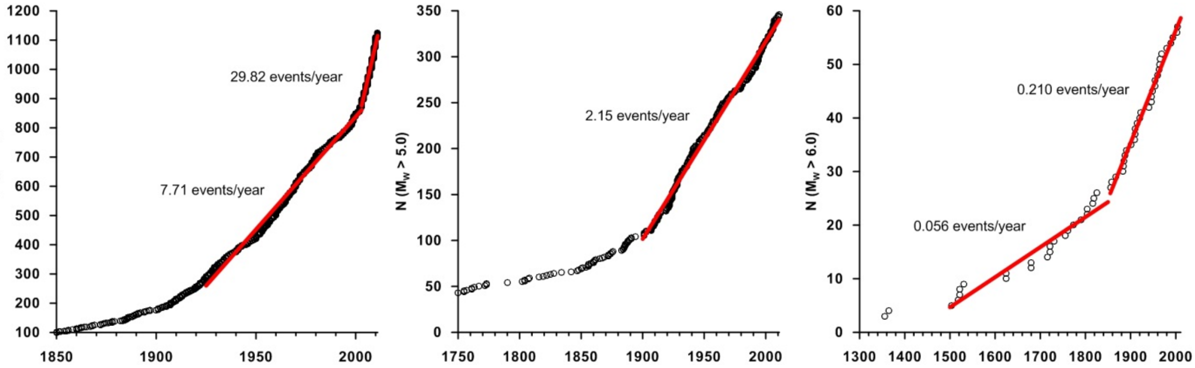

Fig. 2. Number of earthquakes in the final catalog above magnitudes M_W 4.0, 5.0 and 6.0 *vs.* time.

Considering earthquakes since 1900 with magnitude above M_W 5.0 we have obtained an overall *b*-value equal to 0.88 (σ = 0.02). Although there are spatial variations of this parameter in the study region, for this preliminary computation we will consider that it is constant.

We have checked what is the percentage of real events with magnitude equal or above M_W 5.0 occurred within a certain distance of at least one previous event with magnitude in the range M_W 4.0-4.9. We call it percentage of hits, in the line of the works by Kafka and Walcott (1998), Kafka and Levin (2000) and Kafka (2002). Moreover, we have compared it with an aleatory distribution of events with magnitude above M_W 5.0. To compute both percentages, we have used earthquakes with magnitude in the range M_W 4.0-4.9 since 1925 in a region 0.5º smaller in extent than extension of the used catalog, to avoid boundary effects. Must be taken also into account that seismicity in the range M_W 4.0-4.9 from 1925 to 2003 is not complete, then, the computed percentage of hits in all cases will be lesser than the true.

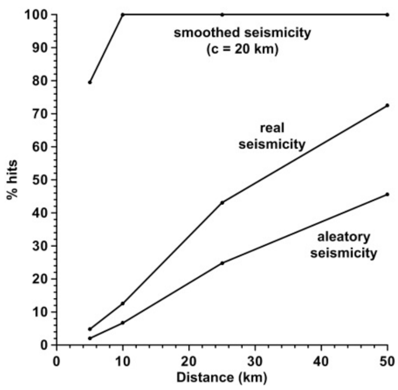

Fig. 3. Percentage of hits (see text).

Evidently, the percentage of hits is dependent on the specified distance to be considered related small and large events (Fig. 3). The main conclusion is that, independently of the considered distance (Fig. 3 shows results for distances less than or equal to 50 km), percentage of hits is significantly greater in the real case that when considering aleatory events, double in the case of specified distances less than

25 km. For example, in a 72.5% of the times, real earthquakes with magnitude greater or equal to M_W 5.0 happened at less than 50 km of at least a previous earthquake in the range M_W 4.0-4.9. In an aleatory (uniform) distribution of earthquakes with magnitude equal or above M_W 5.0, this happens only in a percentage equal to 45.6%. In this last case, were considered all earthquakes in the range M_W 4.0-4.9 since 1925, and aleatory locations for earthquakes above M_W 5.0. Considering in a more detailed simulation not all earthquakes in the range M_W 4.0-4.9 but only previous earthquakes to the aleatory events, the percentage of hits should be significantly lower.

From our catalog, we can say that in the study region it can be observed a relatively good agreement between locations for these two data sets. In fact, considering the previous quoted percentage, nearly 3 out of every 4 earthquakes with magnitude above M_W 5.0 happened since 1925 were located less than 50 km of at least a previous earthquake with magnitude in the range M_W 4.0-4.9. This is the same result that obtained in other regions using different data sets and magnitude intervals (*i.e.*, Helmstetter *et al.*, 2006, 2007; Werner *et al.*, 2011).

Then, we perform a spatial smooth of the seismicity pertaining to the first dataset, that is, earthquakes in the range M_W 4.0-4.9 from 1925 to 2011. Taking into account the uncompleteness for the epoch 1925-2003 for these earthquakes (Fig. 3), we have completed the number of earthquakes in each cell proportionately to the counted number of events in the ranges M_W 4.0-4.9 and for the time period 1925-2003, in order to extent the current mean rate of events until 1925. This process is not necessary to compute the percentage of hits, but essential in order to assess forecasts. We have used square cells with dimensions 10 km x 10 km for which we count directly the number of earthquakes recorded in each of them, and then, we smooth it using a Gaussian filter with a correlation distance c of 20 km. This implies that we spread each earthquake between its own cell and the neighboring: the Gaussian filter cause that, if we associate to the own cell a weight equal to 1.0, the cell distant c contributes with a weight equal to 0.37, and the cell distant $2c$ contributes only with 0.02. Thereby, we take into account errors in the earthquake locations. As was quoted in the introduction section, the main characteristic of this filter is that it preserves the total number of earthquakes. From this result, we have computed again the percentage of hits. It can be also observed in Fig. 3. In order to compare both distributions, the smoothed number of earthquakes as well as earthquakes above magnitude M_W 5.0 are displayed in Fig. 4.

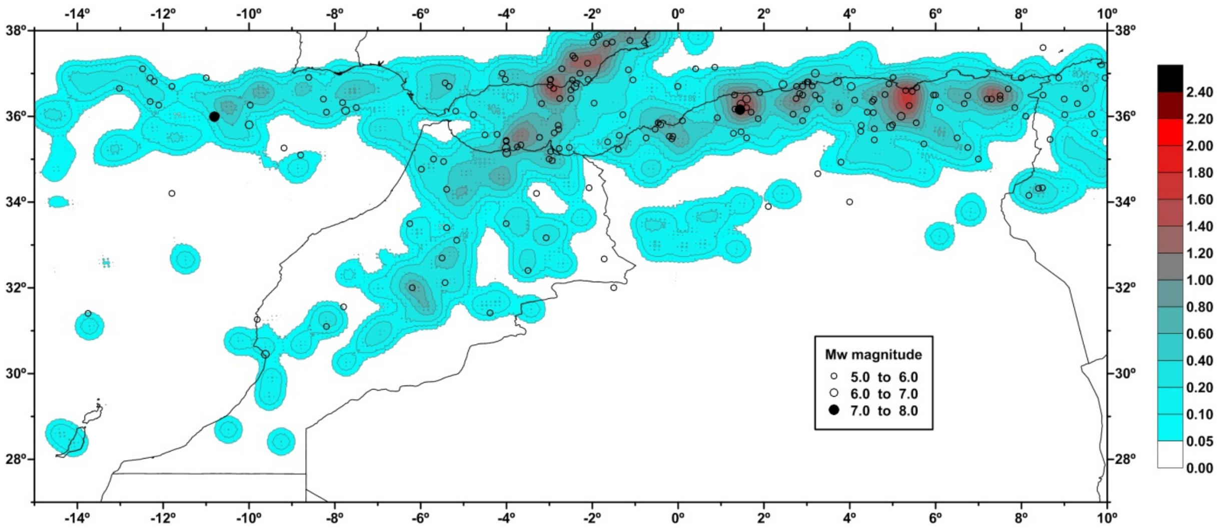

Fig. 4. Smoothed number of events in the range M_W 4.0-4.9 since 1925.
Events above M_W 5.0 are also displayed.

In this case, were considered and smoothed all earthquakes in the range M_W 4.0-4.9 since 1925. Considering in a more detailed simulation not all smoothed seismicity in the range M_W 4.0-4.9 but only previous earthquakes to the aleatory events, the percentage of hits certainly will be lesser.

4. FORECASTING LOCATIONS OF EVENTS WITH MAGNITUDE $M_W \geq 5.0$ AND $M_W \geq 6.0$

The final stage in our assessment is to forecast where will happen large events from the spatially smoothed seismicity. We will consider the smoothed number of events with magnitude above M_W 4.0 in order to compute the yearly number of events in each cell above a certain magnitude value, by using the well-known Gutenberg-Richter recurrence relationship. The a-value is obtained directly from smoothed number of events (correlation distance equal to 20 km), and the used b-value will be the computed regional value. Once yearly number of events is obtained for each cell (n), assuming a Poissonian process, the probability of exceedance for a certain exposure time (T) for the selected magnitude can be obtained from

$$\boldsymbol{P = 1 - e^{-nT}} \tag{4.1}$$

This is the probability per cell. Taking into account cell dimensions, probability per square kilometre can be known multiplying by 0.01.

Probabilities for an exposure time of 10 years can be observed in Fig. 5, for earthquakes with magnitude $M_W \geq 5.0$, and Fig. 6, for earthquakes with magnitude $M_W \geq 6.0$.

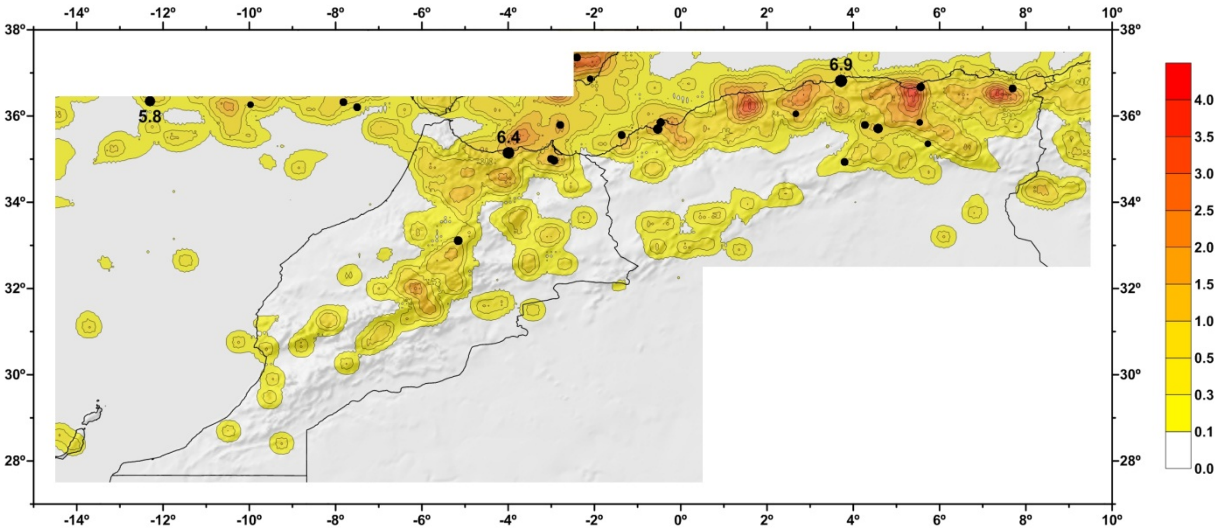

Fig. 5. Probability of exceedance (%) per cell for earthquakes with $M_W \geq 5.0$, in the next 10 years. Events with magnitude above M_W 5.0 located in the last 10 years are also displayed.

In Fig. 5 can be observed maximum values in Northern Algeria in the Tell, and in Northern Morocco mainly in the eastern part of the Rif. Specifically, the following significant maximum values are obtained in different areas (from E to W): 4.06% in Guelma, 3.74% in the N of Setif, 2.55 % in Blida, 3.78% in El Asnam, and 2.23% in the NW of Oran regions, all of them in Algeria, and 2.87% in the NE of Al Hoceima, and 2.48 in the S of the Middle Atlas regions, both of them in Morocco. Other little relative maximum values can be observed throughout the Northern Algeria and Moroccan regions.

To check these results, events with magnitude $M_W \geq 5.0$ in the last 10 years (from 2001 to 2011) have been also displayed. As can be seen, there is a relatively good agreement between locations of these events and forecasted maximum probabilities. The three events with biggest magnitude in the region (the May 2003 Algiers, Algeria, M_W 6.8, the February 2004 N Tamassint, Morocco, M_W 6.4, and the July 2007 Azores-Cape Sant Vincent, M_W 5.8 earthquakes) have been enhanced.

The 2004 N Moroccan earthquake is located in the eastermost part of the Rif, near the area quoted above where maximum probabilities have been obtained in this region. The 2003 N Algerian earthquake is located in the Tell, between two of the areas with relative maximum probabilities, the N of Setif and Blida regions. As can be seen in Fig. 6, these two earthquakes are also included in the areas with biggest probability that earthquakes with magnitude $M_W \geq 6.0$ could happen. In this figure, mostly the Tell and the eastern part of the Rif regions are demarcated clearly as regions where probabilities per cell are in the range 0.1-0.5%. Individual probabilities for these two earthquakes are displayed in Table 4.1.

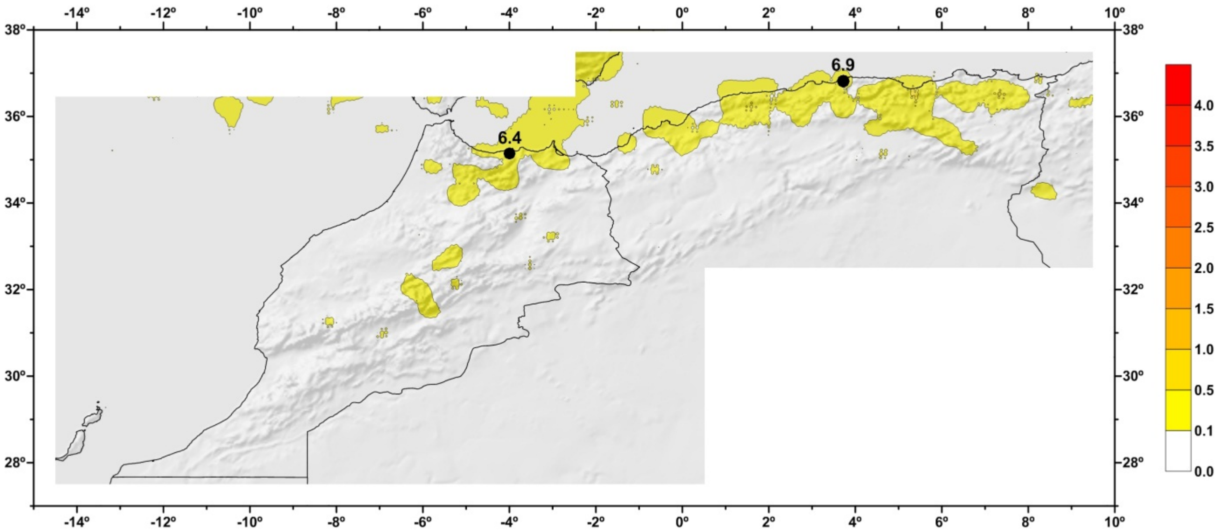

Fig. 6. Probability of exceedance (%) per cell for earthquakes with $M_W \geq 6.0$, in the next 10 years (color scale is the same that in Fig. 5). Events with magnitude above M_W 6.0 located in the last 10 years are also displayed.

Table 4.1. Computed probabilities for the locations of the 2003 Algiers and 2004 N Tamassint earthquakes

	2003 Algiers	2004 N Tamassint
P ($M_W \geq 5.0$)	2.0%	1.3%
P ($M_W \geq 6.0$)	0.3%	0.2%

5. CONCLUSIONS

In Fig. 5 and Fig. 6 are displayed potential areas from a probabilistic point of view to host future earthquakes with magnitudes $M_W \geq 5.0$ and $M_W \geq 6.0$, respectively, in our region of study. The maximum computed values per cell in the region are 4.06% in Guelma, Algeria, and 2.87% in the NE of Al Hoceima, Morocco, when computing the probability of exceedance for earthquakes with $M_W \geq 5.0$ in the following 10 years. Taking into account the known recent mean seismicity rate, 21-22 earthquakes with magnitude above M_W 5.0 and 2 earthquakes with magnitude above M_W 6.0 will happens in this region in the following 10 years.

These results have been obtained using a spatially smoothed seismicity approach and a Poissonian process (earthquake generation process have no memory) considering earthquakes above M_W 4.0 after to check if minor earthquake locations can be used to forecast future places where will happen moderate to large events. An updated earthquake catalog was specifically used for this computation. Although it has a good behavior concerning its completeness and homogeneity, certainly it is the main source of uncertainty in the reliability of the final results.

Certain future refinements (for example, regionalization of the *b*-value) will be considered in the future in order to improve this model.

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