# Stabilizing Intermediate-Term Medium-Range Earthquake Predictions

***V.G. Kossobokov[1,2], L.L. Romashkova[1,2], G.F. Panza[1,3], and A. Peresan[1,3]***

1- The Abdus Salam International Centre for Theoretical Physics, Strada Costiera 11, 34100, Trieste, Italy
2- International Institute of Earthquake Prediction Theory and Mathematical Geophysics, Russian Academy of Sciences, 79/2 Warshavskoye shosse, 113556, Moscow, Russia
3- Department of Earth Sciences, University of Trieste, Via E.Weiss,1, 34127, Trieste, Italy

**ABSTRACT:** *A new scheme for the application of the intermediate-term medium-range earthquake prediction algorithm M8 is proposed. The scheme accounts for the natural distribution of seismic activity, eliminates the subjectivity in the positioning of the areas of investigation and provides additional stability of the predictions with respect to the original variant. According to the retroactive testing in Italy and adjacent regions, this improvement is achieved without any significant change of the alarm volume in comparison with the results published so far.*

**Keywords:** Earthquake predictions; Seismicity; Italy; Algorithm M8

## 1. Introduction.

What is an earthquake prediction? Can we predict earthquakes? These questions remain a subject of numerous controversial discussions and debates [1, 2, 3] but surprisingly of a small number of systematic studies. The United States National Research Council, Panel on Earthquake Prediction of the Committee on Seismology suggested the following definition [4]: "An earthquake prediction must specify the expected magnitude range, the geographical area within which it will occur, and the time interval within which it will happen with sufficient precision so that the ultimate success or failure of the prediction can readily be judged. Only by the careful recording and the analysis of failures as well as successes can the eventual success of the total effort be evaluated and future directions charted."

According to this definition the accuracy of the prediction of an earthquake of a certain magnitude range may differ in the duration of the time interval and/or in the territorial dimension. A temporal classification, which distinguishes long-term (for decades), intermediate-term (for years), short-term (for weeks), and immediate (for days and less) predictions is commonly accepted. Following the common perception it is easy to overlook the option of spatial modes of predictions and to concentrate efforts attempting to decide when the "exact" fault segment is going to rupture, e.g. as it was done in the Parkfield earthquake prediction experiment [5, 6]. This is far more difficult than predicting large earthquakes with lesser spatial accuracy and might be an unsolvable problem. On the other hand, it is natural to suggest that the preparation of the target earthquake is taking place at distances much larger than its source zone. In such a case, its precursors should be searched in a wider area that exceeds significantly the source of the incipient earthquake. For example, Press and Allen in [7] demonstrated that the area involved in the formation of precursors may exceed the rupture length of the expected earthquake by a factor of 50 or more. Considering larger areas may eventually help avoid the deficiency of data used to describe the state of the system at the approach of a catastrophe and, therefore, makes the efficient prediction of large earthquakes possible.

When related to the rupture length $L$ of the target earthquake, spatial prediction modes could distinguish, besides the “exact” location of a source zone, wider ranges of territorial certainty, which are listed in Table (1). These modes, being less specific, allow for a robust and a more stable description of the system, which, in its turn, implies a more reliable prediction of a catastrophe.

**Table 1.** Prediction accuracy

| Temporal (in Years) | | Spatial (In Source Zone Size L) | |
|---|---|---|---|
| Long-Term | 10 | Long-Range | Up to 100 |
| Intermediate-Term | 1 | Medium-Range | 5-10 |
| Short-Term | 0.01-0.1 | Narrow | 2-3 |
| Immediate | 0.001 | Exact | 1 |

The reproducible earthquake prediction algorithm, named *M*8 [8], fully agrees with the general definition [4] and essentially it provides predictions of Intermediate-Term medium-range accuracy. On the contrary, probability mappings by Kagan and Jackson [9], which might be useful in many practical applications, are not earthquake predictions in this sense: for a given mapping the ultimate success or failure cannot be judged without setting, in advance, the exact value of the probability cut-off that determines an alarm and the target magnitude range. A probability mapping also assumes some probability model that must be justified as well.

The algorithm *M*8 fulfills all the necessary preconditions for a scientific testing:

1) Its ultimate description, that is the computer code, was published and distributed since its origination [10, 11];
2) At least some of the routine seismic catalogues are complete enough for a real time application of “black-box” versions of *M*8 that guarantee the absence of human intervention;
3) The prediction results are unambiguous and permit an easy comparison with the null-hypothesis of random recurrence of earthquake epicenters in places where they were reported.

Based on a sequence of earthquakes from a specified location, *M*8 algorithm was designed to overcome some unavoidable errors in seismic data, such as the incompleteness at low magnitudes. In this respect the key features of the *M*8 algorithm are the following:

1) The counts used for prediction are robust intermediate-term medium-range average measures of the seismic activity and are repeated in different magnitude ranges,
2) The cut-off values – different thresholds and percentiles - are determined in a robust way without optimization or data-fitting, and,
3) The decision about starting an alarm requires the confirmation of diagnosis in two consequent moments of time.

However, some external ways of stabilizing the prediction have not been investigated enough, so far. Minster and Williams in [12] did reprogramme the *M*8 algorithm in a form that permitted the random variations in some of its internal parameters. Using a Monte Carlo approach they checked the stability of two predictions – the 1989 Loma Prieta and 1992 Landers earthquakes in California – made by the *M*8 algorithm concluding, “that the algorithm is indeed triggered by large seismicity fluctuations apparent in the catalogue.” Unfortunately, further investigations by Minster and Williams in [13] regarding the global testing of *M*8 algorithm deal with an over averaged measure of “likelihood”, which is used to define the “likelihood” method predictions. The measure actually originates from multiple applications of the *M*8 algorithm with randomized initial settings, including random positioning of circles of investigations. However, it completely neglects the apparent heterogeneity of earthquake locations. In this paper we will try to show, on the example of Italy, how a more delicate stabilizing procedure based on natural earthquake distribution may improve the stability and, in its turn, the reliability of *M*8 predictions, without any essential change of accuracy.

## 2. M8 Algorithm

The algorithm *M*8 [14] is based on the hypothesis of precursory intermediate-term medium-range activation of seismic flow prior to a large event. Algorithm *M*8 uses the catalogue of moderate main shocks and calculates seven functions of seismic activity inside circles of investigation, *CI’s*, of radius normalized by the linear size of the incipient event, target of the prediction. These functions characterize the rate of seismic activity, the change of a longer-term trend of seismic activity, linear concentration of sources and clustering of earthquakes. An alarm, the time of increased probability for the occurrence of a large earthquake, is declared for 5 years at the moment when most of the seven functions reach anomalously high values during the preceding 3 years. Algorithm *M*8 was designed for predicting the strongest world earthquakes with magnitude 8.0 and above [8], and was adapted later to the prediction of earthquakes with smaller magnitudes [14].

Each application of *M*8 algorithm starts with the definition of *strong earthquake*, as the target one we aim to predict, with the condition that its magnitude $M$ is greater or equal to the threshold $M_0$. Naturally, the magnitude scale should reflect the size of the earthquake sources. Accordingly, $M_s$ (surface wave magnitude) is usually taken for larger events, while $m_b$ (body wave magnitude) is used for smaller ones, for which $M_s$ determinations are infrequent and mostly not available. For many catalogues, using the maximum reported magnitude, $M_{max}$, could set this up. We do so, at global scale, when using the National Earthquake Information Center/U.S. Geological Survey Global Hypocenters' Data Base and, at regional scale, when using the *UCI*2001 catalogue for Italy, Peresan and Panza [21].

In most cases the choice of $M_0$ is predetermined by the condition that the average recurrence time of strong earthquakes is sufficiently long in the territory considered. In order to establish a value of $M_0$ for a seismic territory, we consider values of $M_0$ with an increment 0.5, unless the actual distribution of earthquake size suggests a natural cut-off magnitude that determines the characteristic earthquakes. The radius of *CI's* is a certain function of the size of the targeted earthquakes and, therefore, of $M_0$. When the data permit the application of the *M*8 algorithm for the prediction of earthquakes above many magnitude thresholds $M_0$, the size of *CI's* appropriate for the smaller values of $M_0$ becomes no longer representative of the preparation processes in the larger magnitude ranges. Therefore, the analysis should distinguish a number of intervals $M_0 \leq M < M_0 + \Delta M$ indicated as $M_0+$ and deliver a hierarchy of predictions related to the corresponding magnitude ranges $M_0+$. The change in definition of strong earthquakes-from $M \geq M_0$ to $M_0 \leq M < M_0 + \Delta M$ - is a natural implication of the medium-range accuracy of the *M*8 algorithm. The width of the magnitude range $M_0+$, i.e. $\Delta M$, should characterize the accuracy in the relation between the magnitude $M_0$ and the rupture size $L(M_0)$. In practical applications $\Delta M = 0.5$ might be small, while $\Delta M = 1$ might be excessive already (such a large value eventually violates the limits of the spatial mode of prediction delivered by the algorithm).

There is another essential modification that has never been used before and should now be introduced. That is the size of a trailing window that defines a part of the catalogue considered in the application of *M*8. Until recently there was no need for such a window due to the rather limited temporal span of the catalogues available. The standard test of algorithm *M*8 [10] uses the whole catalogue of main shocks from the beginning, determined by its completeness (e.g., 1963 for *NEIC* data), up to the current date. In Italy we have the beginning of the catalogue in 1950. In such a case, when we simulate retroactively the forward prediction in 1972-2001 the window of the catalogue used changes by more than a factor of 2, from 22 years to 50 years. In the future the size of catalogues would increase at no allowance. Thus, it is necessary to introduce a certain size of the catalogue span. In Italy we fix the parameter by setting a trailing window size at 30 years. It is time to introduce the trailing window of the catalogue span in the world-wide test of *M*8 [10, 16] as well.

The global test of the algorithm *M*8 [10] aimed at the prediction of the largest earthquakes (those defined by $M_0$=7.5 and $M_0$=8.0) has been carried out routinely [17] in real time for at least 10 years now (a complete record of predictions in 1985-2001 can be viewed at http://mitp.ru/predictions.html). The test demonstrated [16] the statistical significance of advanced predictions of the largest earthquakes in the Circum-Pacific. Besides that, in the regions where the completeness of seismic data is sufficiently high, the algorithm succeeded in applications aimed at the prediction of earthquakes with the threshold $M_0$ as low as 4.9 [14]. In a few cases, when the regional catalogues available were not providing enough data for the standard version of *M*8 algorithm, a variant of *M*8 has been applied with a predictive effectiveness [18, 19, 20]. In this variant the value of the requested recurrence rate of the main shocks in the areas of investigation, $\tilde{N}$, is reduced from the standard 20 events per year to a smaller number. All other parameters of the algorithm are not changed, thus limiting the potential freedom of data fitting to one dimension only.

## 3. Complexity of Seismic Distribution and Complications in M8 Applications

The seismic activity is not distributed uniformly. There is an evident pattern in the spatial distribution, which is restricted to the well-known major seismic belts on global scale. On finer regional scales the pattern is claimed to show up active faults. This pattern displays a certain similarity when consequently zoomed. Such a similarity supported by different counts, although based on a finite number of epicentres of recorded earthquakes, suggests the self-similar, fractal structure of the earthquake-prone locations [22, 23].

Given a reproducible earthquake prediction algorithm (e.g. *M*8) one may try to apply it in any place where data permits [12, 13]. This apparently natural trial may obscure the researcher because of the above-mentioned heterogeneity of seismic distribution. Indeed, when an extended area of investigation (e.g. a *CI*) is positioned independently from the places where earthquakes occur, its size may become irrelevant with respect to the size of the seismic zone inside it. The difference of sizes is large in particular when just a small section of the area of investigation overlaps the seismic zone. In such a case the analysis is biased and obscuring, that is why its effortless interpretation may generate confusion. It is natural to assume that the area of preparation is a function of the target earthquakes dimension. For example, this assumption is used in *M*8 algorithm for setting the radius of *CI's*. To avoid bias in the analysis it is essential to place the centres of *CI's* on the axes of the seismic distribution in space. Moreover, the territorial limits of the catalogue's completeness, in particular for regional catalogues, add complications to the adequate distribution of the areas of investigation [16].

## 4. Area of Alarm

In the standard application of *M*8 algorithm the circles of investigation are placed along the line of maximal concentration of seismic epicenters, so that to cover all seismic-prone territory of the region considered with approximately three-times-overlap. The position of the *CI's* and accordingly their number, remains a rather arbitrary choice, which requires answers to the two questions:

1) How to arrange the circles in each particular region?
2) How to attribute an alarm in a multiple overlap of the circles?

In the practice of the *M*8 algorithm applications the answer to the second question is a single alarm, with the same degree of hazard over the space union of several overlapping alarms declared. In practical applications earthquake prediction results deliver temporal variability to estimations of seismic hazard and/or risk: to estimate the time-dependent seismic hazard the alarm should be appropriately convolved with the term-less distribution of earthquake-prone areas, while for the estimation of the time-dependent seismic risk the result requires additional convolution with the distribution(s) of population and/or economy.

The first question is more difficult, since the general rule for the positioning of the circles on the axes of the seismic distribution in space gives a rather wide freedom in the choice of each appointed circle. When a small number of circles is fixed in the region, which is the existing practice of the real-time monitoring, the problem of the prediction stability with respect to the positioning of *CI's* remains open. Naturally the stability and reliability of the alarm can be tested by systematic variations that imply automatic setting of *CI's* at the nodes of a dense grid and deliver a possible answer to the first question. In the next section we introduce the scheme that makes use of the natural heterogeneity of earthquake distribution and essentially stabilizes *M*8 predictions.

## 5. Scheme of Spatial Stabilization and Its Application in Italy

Taking into account the considerations and the experience described in the previous sections a new scheme for the spatial stabilization of the *M*8 prediction is suggested [15]. It depends less on the positioning of a particular circle and regularizes the declaration of alarms. A description of the new scheme is as follows:

❖ Consider the territory covered by data from a given catalogue and exclude the band of about $1^0$ near its boundary. For Italy this territory, outlined by the *UCI*2001 catalogue [21], increases gradually from1950 to 2001 due to the improvement of the catalogue completeness and, to be conservative, we consider the one valid for 1950, which spans within $38^0N$-$47^0N$ and $7^0E$-$17^0E$.

❖ Scan the territory with small circles distributed over a fine grid and find all local seismically active places, keeping the grid points with the average annual rate of seismic activity, in the circle, above a certain threshold. For Italy the grid spacing is $0.25^0$ by $0.25^0$, the radius of circles equals 28*km*, and the activity cut-off is set at 0.3 main shocks of magnitude 3 or above per year.

❖ Exclude the grid points where the data are insufficient for the application of *M*8 algorithm and then remove isolated grid points and pairs.

❖ Apply *M*8 algorithm using the circles of investigations, *CI's*, centred on each of the remaining grid points.

- Remove the alarm circles centred at the grid points that do not satisfy the following clustering condition: the overwhelming majority of the *CI's*, centred at the neighbouring grid points that remain in the analysis, are in state of alarm. For Italy the overwhelming majority is defined by 75% of the remaining neighbouring grid points from a 3×3-grid square.

Naturally, some free parameters are present in this scheme. The first two are the radius of the small circle, which is used to find the local seismically active places, and the level of seismic activity within it (some sort of characterization of the seismic density). These parameters determine the way we outline a seismically active territory. By changing them, it is possible to get a more or less broad zone for the analysis. We think that it is appropriate to fix them at values giving a rather thin pattern of seismic belts along the whole territory of investigation. The third parameter is the grid spacing, whose size is close to the radius of the small circle and should be related to the dimension of target earthquakes. In Italy we use a rectangular grid with the same spacing of $0.25^0$, both in latitude and longitude. The fourth parameter defines what is the overwhelming majority of the neighbor grid points in the clustering condition.

Of course the choice of these parameters could be different in different regions and we recommend varying them when designing a new test, in order to obtain the most possible stable retrospective prediction results, as was done for the territory of Italy [15]. Figure (1) shows the grid points singled out as on 2001.01.01, with the described procedure, for the prediction experiment with $M_0$=6.5. Each dot corresponds to a grid point remaining after the exclusion of the isolated ones, which is, accordingly, the centre of a circle of investigation.

The new methodology, when applied to Italy and surroundings within $38^0N$-$47^0N$ and $7^0E$-$17^0E$, provides the results summarized in Table (2). There are four main shocks with magnitude 6.0 and above in 1950-2000, inside the area considered, see Figure (2).

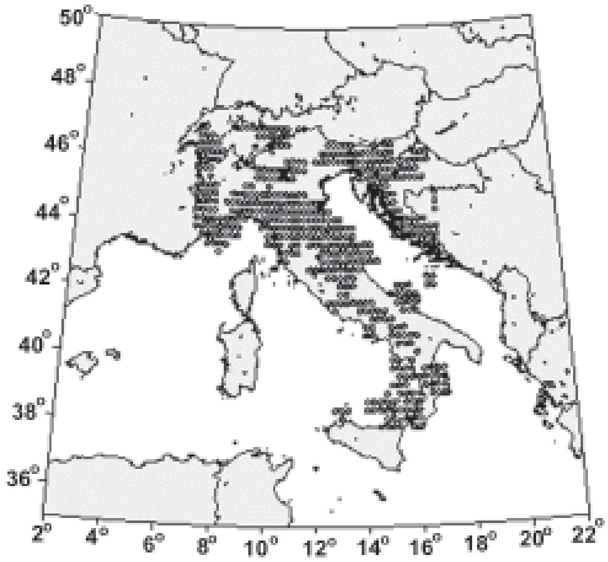


**Figure 1.** The territory singled out by the procedure, as on 2001.01.01, for the prediction of earthquakes with magnitude 6.5 and above. Each dot corresponds to the center of a circle of investigation to which the M8 algorithm is applied.

Three of them occurred in Italy (Friuli, Irpinia, and Assisi) and the last one near its border (Bovec, Slovenia).

To simulate retroactively a forward prediction experiment using the scheme described above, we run *M*8 each half-year, from January 1972 to January, 2001, in circles whose centres are defined automatically from the distribution of earthquakes. We make predictions in the two different magnitude ranges defined by $M_0$ = 6.5 and 6.0, which are referred to as *M*6.5+ and *M*6.0+ below.

Figure (2) illustrates the results of the application of the *M*8 algorithm to the prediction of large earthquakes in Italy. The grey circles, both light and dark, outline the territory where the algorithm *M*8 has been applied; the dark ones display the alarm area. The retrospective predictions of the Friuli and Irpinia earthquakes are given in Figures (2a) and (2b). The Assisi and Bovec earthquakes are separated in time by nearly half-year, so that they fall in subsequent periods of analysis, which are characterized by the same two areas of increased probability of large

**Table 2.** Main shocks in Italy and adjacent territory with M ≥ 6.0, 1986-2000.

| Region | Date | Latitude, N | Longitude, E | Depth | M | Prediction |
|---|---|---|---|---|---|---|
| Friuli | 1976.05.06 | 46.23 | 13.13 | 12 | 6.5 | Yes |
| Irpinia | 1980.11.23 | 40.85 | 15.28 | 18 | 6.7 | Yes |
| Assisi | 1997.09.26 | 43.08 | 12.81 | 10 | 6.4 | No |
| Bovec | 1998.04.12 | 46.24 | 13.65 | 10 | 6.0 | Yes |

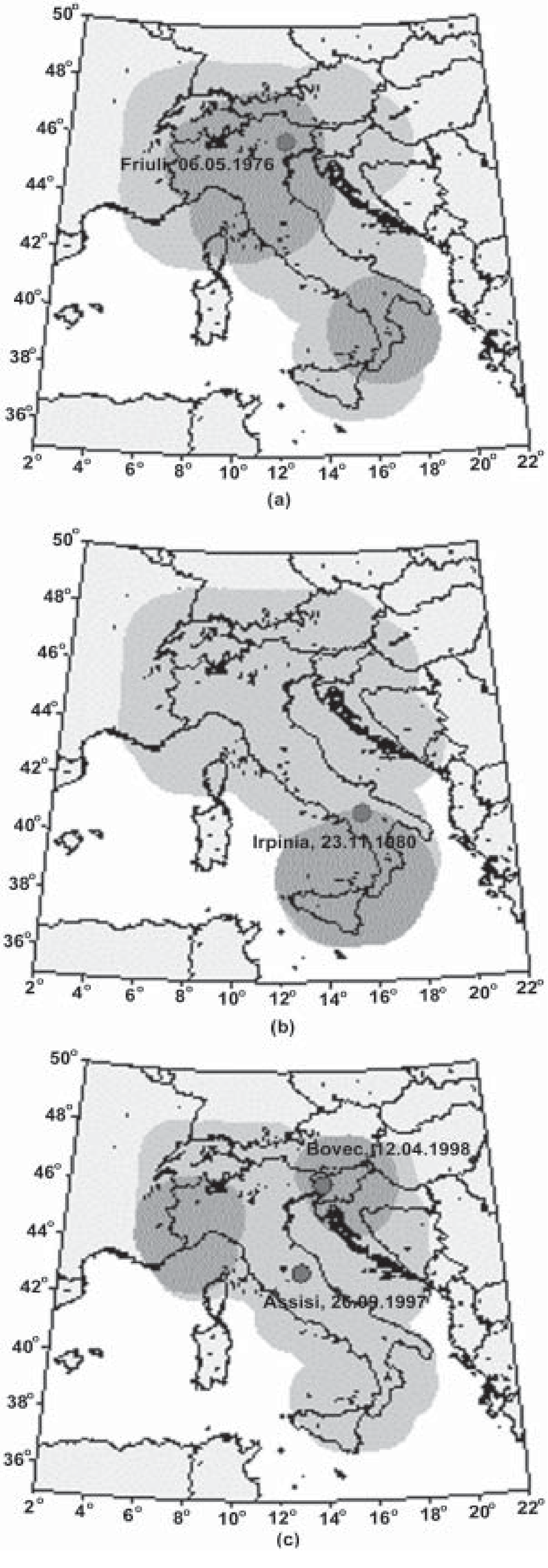


**Figure 2.** Results of the prediction obtained with the new space stabilized variant of algorithm M8. Application in Italy for $M_0$= 6.5 before (a) the Friuli 1976, $M_{max}$= 6.5 and (b) the Irpinia 1980, $M_{max}$= 6.7 earthquakes. (c) Same for $M_0$= 6.0 before the Bovec 1998, $M_{max}$= 6.0 earthquake, $M_{max}$ is the largest value of the magnitudes reported for each event.

earthquakes, see Figure (2c). One of the alarm areas covers the epicentre of Bovec earthquake. Figure (3) shows the current (at the time of writing this paper) alarms in Italy as on 2001.07.01: there is a rather large territory in state of alarm in the northern part of Italy for both magnitude ranges *M*6.5+ and *M*6.0+. The area for *M*6.5+ , Figure (3a), is larger than that for *M*6.0+, Figure (3b). The Friuli region is inside the alarm area for the larger magnitude range but outside the alarm for the lower one.

The average space-time volume of alarm in percent to the total equals 38.6% for *M*6.5+ and 29.6% for *M*6.0+. A few words explaining the way we compute the space-time volume of alarm is necessary because it is rather unusual in publications and it accounts for

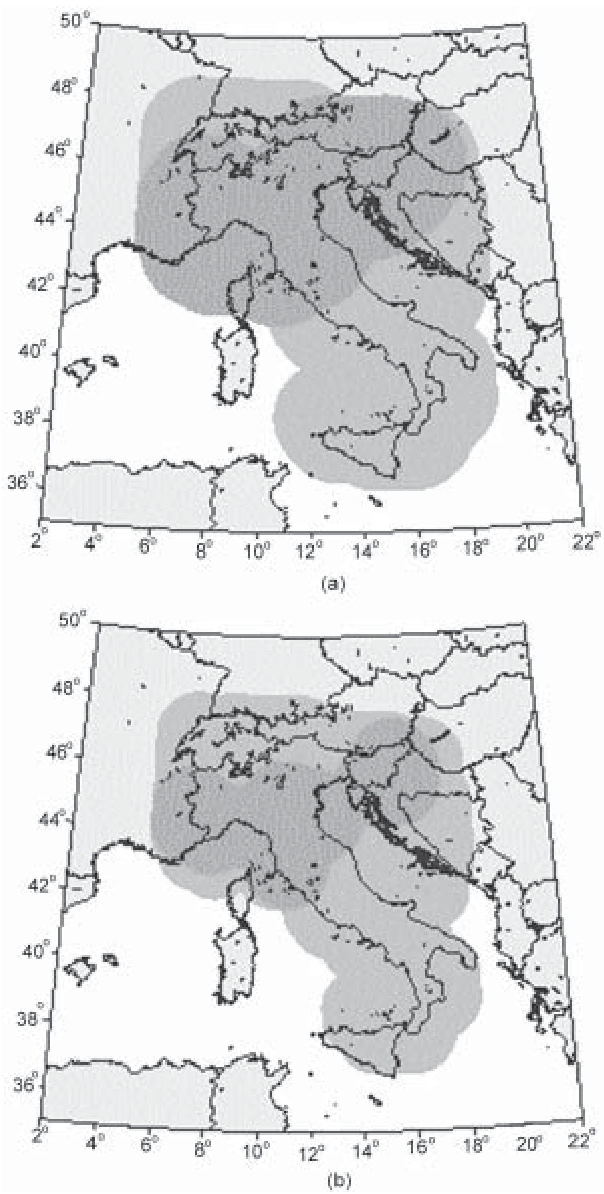


**Figure 3.** The current alarms determined with algorithm *M*8 in Italy, as on 2001.07.01 (subject to update in January 2002), for (a) $M_0$=6.5 and (b) $M_0$=6.0.

the actual distribution of seismic activity in the region. Consider a "sample catalogue" representative of the seismic activity of the territory under study. At a given time, we define the spatial percentage of alarm as the ratio of the number of epicenters from the sample catalogue, which fall inside the area of alarm, to the total number of epicenters, which fall inside the union of all circles of investigation. The space-time volume of alarm is then computed as the average spatial percentage of alarm over the total period of diagnosis. In the case of Italy we use, as a sample catalogue, all earthquakes of magnitude 4.0 or more contained in the UCI2001 catalogue, for the period 1950-2000.

It is possible to get a smaller value of the space-time volume of alarm using a more rigid clustering parameter [15]. In such a case the same three earthquakes as in the main experiment are predicted with the space-time volume of alarm decreased by about 4%. However, it is known that in the analysis of small samples there is always a trade-off between parameter fitting and the reliability of future real-time application. The way to verify our choice of the clustering parameter is the advance prediction of Italian earthquakes from lower magnitude ranges, or the application of the new variant of M8 algorithm in regions similar to Italy from the seismic and tectonic viewpoint.

## 6. Discussion and Conclusion

We have designed a new spatially stabilized scheme of predictions made with algorithm *M*8 and we have applied it retrospectively to the Italian data for the period 1972-2001. The new variant of *M*8 allowed us to avoid random alarms and to increase the stability and reliability of the prediction. We gained stability of predictions without any significant change of the alarm volume, so that the efficiency of the algorithm is basically preserved. Comparing our results with those of the "likelihood" method [12, 13] shows that taking into account the natural distribution of seismic activity may help recovering the original efficiency of the *M*8 algorithm, which was lost in its "bootstrapped" offspring.

In the new variant the space-time volume of alarm for *M*6.5+ is larger than for *M*6.0+, contrary to the results of the previous applications of *M*8 algorithm in Italy [24], where the application to predict smaller magnitude earthquakes, produced a relatively larger space-time volume of alarm. The behaviour of the standard variant [24] might seem more natural than that of the new one, however the reversed relation between $M_0$ and relative space-time volume of alarm can be explained by some independence in the preparation processes at different, even neighbouring, levels of the seismic hierarchy. Among other possible explanations of such behaviour is the introduction in the new variant of additional free parameters, which might have been normalized improperly. Specifically, the grid spacing is not independent of $M_0$ and essentially affects the clustering parameter. When we decrease $M_0$ the area of preparation of the target earthquake gets smaller. In an unchanged grid, this leads to a smaller number of circles in alarm, which locally may become not sufficient to form the overwhelming majority even in case of a true alarm. Thus, the parameter of clustering, if unchanged, eventually becomes more restrictive. On the other hand, a proper rescaling would require:

a) Appropriate changes of the grid spacing and of the radius of the small circles, in proportion to the source dimension of the target earthquake,
b) A smaller magnitude cut-off, used for outlining the seismically active territory. This requires the lowering of the completeness magnitude threshold. In the presented application of the new spatially stabilized variant of *M*8 algorithm in Italy, we did not make any rescaling of the grid, on account of the small variation of $M_0$ (0.5).

## Acknowledgements

This research has been supported by the International Science and Technology Center (Project 1538-00), by the Russian Foundation for Basic Research (grant #00-15-98507), and by the James S. McDonnell Foundation (the 21st Century Collaborative Activity Award for Studying Complex Systems, project "Understanding and Prediction of Critical Transitions in Complex Systems"). This is a contribution to the *MIUR-COFINANZIAMENTO* projects 1999 and 2000, to the *UNESCO-IUGS-IGCP* Project 414 and to the *NATO SFP* project 972266.

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