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Analysis of Earthquake Catalogs for Earthquake Prediction Purposes

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Stability of intermediate-term earthquake predictions with respect to random errors in magnitude: the case of central Italy

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Abstract

The influence of random magnitude errors on the results of intermediate-term earthquake predictions is analyzed in this study. The particular case of predictions performed using the algorithm CN in central Italy is considered. The magnitudes of all events reported in the original catalog (OC) are randomly perturbed within the range of the expected errors, thus generating a set of randomized catalogs. The results of predictions for the original and the randomized catalogs, performed following the standard CN rules, are then compared. The average prediction quality of the algorithm CN appear stable with respect to magnitude errors up to ±0.3 units. Such a stable prediction is assured if the threshold setting period corresponds to a time interval sufficiently long and representative of the seismic activity within the region, while if the threshold setting period is too short, the average quality of CN decreases linearly for increasing maximum error in magnitude.

Keywords: Earthquake prediction; Algorithm CN; Magnitude error; Randomization; Italy

1. Introduction

A generation of intermediate-term earthquake prediction algorithms was developed and exhaustively tested during the past two decades (Gabrielov et al., 1986; Keilis-Borok, 1990; Minster and Williams, 1992; Keilis-Borok and Shebalin, 1999; Kossobokov et al., 1999; Rotwain and Novikova, 1999; Vorobieva, 1999). The empirical nature of these algorithms, however, makes it difficult to evaluate their efficiency and strength in a formal way, due to the long time required for the tests in real predictions and to the possible over-fitting in retrospective studies. This stimulated the development of different specific methods for the evaluation of algorithms quality (Habermann and Creamer, 1994; Minster and Williams, 1992; Keilis-Borok and Shebalin, 1999). One relevant question that still needs to be answered is: to what extent are predictions influenced by the unavoidable errors affecting the input data?

Earthquake catalogs represent the most widely available geophysical data, containing systematically collected information about seismicity. This is why most of the studies concerning precursory phenomena, and therefore earthquake predictions, are based on the analysis of earthquake catalogs. The catalogs contain errors which can be distinguished into systematic and random ones (this is comprehensively

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discussed by Kossobokov, 1995). Systematic errors can be associated to changes in the data acquisition system or in the methods for the determination of earthquake parameters. Random errors correspond generally to the uncertainty of determination and to possible mistakes made during the data input process. The presence of a systematic error in magnitude may hamper prediction results and is generally quite difficult to detect (Habermann, 1991; Habermann and Creamer, 1994; Kossobokov and Shebalin, 1995); some aspects of this problem for the Italian catalog have been considered by Peresan et al. (2000).

The goal of this work is to study the influence on the results of intermediate-term earthquake prediction of random errors in magnitude determination. We analyze here the particular case of earthquake predictions performed by CN algorithm (Keilis-Borok and Rotwain, 1990). The algorithm uses origin time, hypocentral coordinates and magnitude of earthquakes. Among these parameters, magnitude is the most significant source of errors in the results of predictions, because it enters in the determination of the values of the functions describing the seismic sequence as well as in the definition of the strong earthquakes (Rotwain and Novikova, 1999).

Our analysis is based on the predictions performed for central Italy (Peresan et al., 1999b). To establish the dependence of the prediction results on possible random errors in magnitude, the algorithm CN is applied to several "randomized" catalogs (RC). These RC are obtained by random modification, within the range of the assumed errors, of the magnitudes of all events. The results of predictions obtained for the original catalog (OC) and the RCs are compared, providing useful information about the stability and the expected performances of the algorithm.

2. General scheme of prediction with CN algorithm

The algorithm CN has been designed for the prediction of *strong earthquakes*, which are the events with magnitude greater or equal to a fixed threshold M_0. The algorithm is based on the analysis of a set of empirical functions describing the earthquake flow. These functions are normalized by thresholds in magnitude, which are selected on the basis of the average return period of events observed during the *thresholds setting period*. The functions are discretized into small, medium and large values, accordingly to the level of seismic activity in the considered region, and the thresholds for discretization are selected by the retrospective analysis of seismicity within the thresholds setting period. The discretization of functions causes some loss of information, but makes the algorithm more robust with respect to fluctuations in the data. The thresholds setting period must correspond to an interval of time long enough to provide a representative sample of the seismic activity within the considered region, including periods of quiescence as well as periods of high activity (Keilis-Borok and Rotwain, 1990).

The algorithm CN identifies the times of increased probability (TIPs) for the occurrence of strong earthquakes. When a strong event occurs during a TIP, then it is indicated as a *successful prediction*, otherwise it is referred as *failure to predict*. If no strong earthquake occurs during a declared TIP, then the TIP is called a *false alarm*.

According to Molchan (1990), the results of a prediction can be characterized by two types of errors. The first one is the percentage η of failures to predict: $\eta = F/N$, where F is the number of failures to predict and N the number of events to be predicted. The second one is the percentage τ of the total duration of alarms: $\tau = A/T$, where A is the total duration of alarms and T the length of the whole time interval considered. The strength of a prediction is estimated by the analysis of the *error diagram*, collecting information on both types of errors. According to Molchan (1990, 1996), in order to characterize the quality of predictions in terms of the errors η and τ, it is possible to consider any convex function $\Omega = f(\eta, \tau)$. Among the several possible functions, the sum of errors appears to be the most straightforward and suitable for the evaluation of the outcomes, as recommended by Molchan (1996). Hence, in the present analysis the quality of predictions will be quantified by the sum of errors: $\Omega = \eta + \tau$. Since the random prediction gives $\Omega = 1$ (Molchan, 1990), one can roughly estimate the quality of prediction by the deviation of Ω from unity (or from the corresponding percentage $\Omega = 100\%$).

3. Magnitude randomization procedure

The procedure of magnitude randomization simulates possible random magnitude errors in the analyzed catalog. In the present study, we concentrate on two types of random errors: the error of *measurement* and the errors of magnitude *discretization*.

The value of magnitude reported in the catalog is usually the result of estimations made from several stations recording the occurrence of an earthquake. The error of measurement represents the several factors (radiation pattern, local effects, etc.) that may influence the records of an event at different stations and consequently affect the magnitude estimation. We use here a rough assumption that the final measurement error ΔM_M is normally distributed. Since the observed magnitude is finite, we use for ΔM_M the truncated normal distribution $F^{TR}(x)$, that is defined on the interval $x \in [-\Delta M_{max}, \Delta M_{max}]$ as

$$F^{TR}(x) = \frac{F(x) - F(\Delta M_{max})}{F(\Delta M_{max}) - F(-\Delta M_{max})} = \frac{F(x) - F(\Delta M_{max})}{2F(\Delta M_{max}) - 1} \quad (1)$$

where $F(x)$ denotes the cumulative normal distribution with 0 mean and S.D. $= \Delta M_{max}/3$. The measurement error ΔM_M thus becomes normally distributed on the interval $[-\Delta M_{max}, \Delta M_{max}]$ while the values outside this interval are disallowed.

The values of magnitudes are calculated as real numbers with several digits, but their precision hardly exceeds the first decimal digit (e.g. the magnitudes calculated from intensity, which is a discrete scale, exhibit a discrete distribution); for this reason the measured values are usually rounded, i.e. they are discretized to fit some predefined lattice. Let M_C be the operating magnitude selected from the catalog and k the step of the discretization lattice, when discretizing (i.e. rounding) the magnitude, an error as large as $\pm k/2$ can be introduced. Since the measured magnitude may correspond to any of the values in the magnitude interval $[M_C - (k/2), M_C + (k/2))$, then we assume that the error of magnitude discretization ΔM_K has a uniform distribution within the interval $[-k/2, k/2]$.

Considering the quantities M_C, ΔM_M, and ΔM_K defined earlier, we introduce the randomized magnitude M_R

$$M_R = M_C + \Delta M_M + \Delta M_K \quad (2)$$

where the measurement error ΔM_M and the error of discretization ΔM_K are independent.

4. Data analysis

4.1. Numerical parameters for randomization

The randomization procedure, introduced in Section 3, depends on two parameters: k and ΔM_{max}. The parameter k is uniquely determined by the used catalog, which is fully described by Peresan et al. (1999a).

The catalog is composed by the CCI1996 (Peresan et al., 1997) for the period 1900–1985, and is updated using the NEIC preliminary determinations of epicentres (PDE) since 1986. The operating magnitude in the catalog CCI1996 is selected according to the following priority order: M_L, M_d, M_I (Molchan et al., 1997), where M_L is the local magnitude, M_d the duration magnitude and M_I the magnitude from intensities. A corresponding priority choice has been defined for the magnitudes in the PDE catalogue as follows: $M2$, $M1$, M_s. The magnitude from the surface waves estimated by NEIC is given by M_s, while $M1$ and $M2$ correspond to magnitudes of different kind, supplied by different agencies, mainly corresponding to local and duration magnitudes (Peresan et al., 1999a and references therein).

The number of earthquakes in different magnitude intervals and for three time periods (1950–1980, 1980–1999 and for the entire interval 1950–1999) is given in Fig. 1. It is possible to observe that since 1950 the magnitudes are determined to the first decimal digit, hence the discretization step is $k = 0.1$.

The second parameter of randomization, ΔM_{max}, is a variable one. According to Båth (1973), from empirical observations we can expect errors as large as ± 0.3 units in reported magnitudes; such a value is confirmed by theoretical arguments (Panza and Calcagnile, 1974; Herak et al., 2001). Hence, in the present study we will assume $\Delta M_{max} = 0.3$ as an upper bound for realistic errors in magnitude. Larger values for ΔM_{max} are considered in order to evaluate the dependence on ΔM_{max} of the quality of the results. The randomization procedure is applied to the OC, varying the parameter

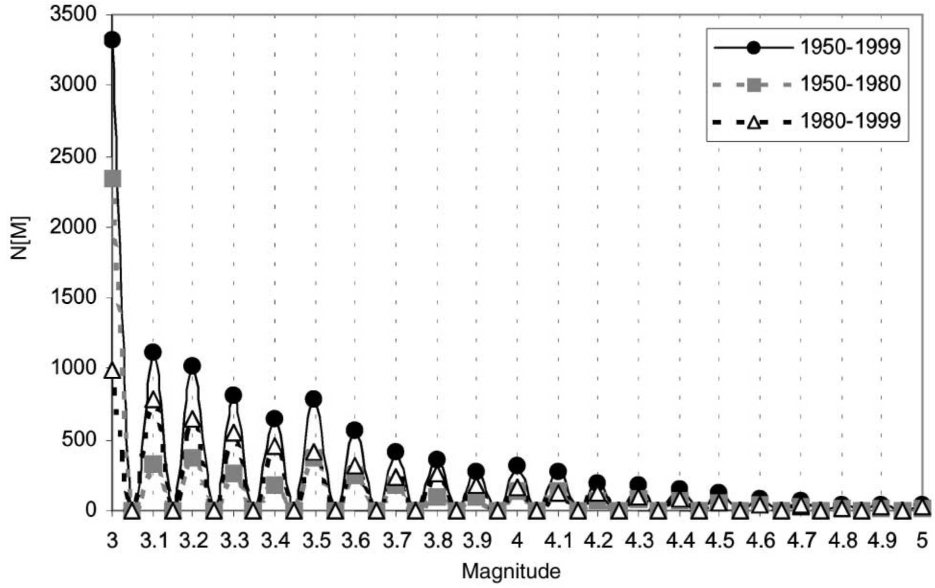

Fig. 1. Number of earthquakes with $3 \leq M \leq 5$ reported in the OC (Peresan et al., 1999a) for three different periods of time: 1950–1980, 1980–1999 and 1950–1999.

$\Delta M_{\max}$, and a set of 110 RCs is generated: 30 catalogs for $\Delta M_{\max} = 0.1$, 0.2 and 0.3, plus 10 catalogs for $\Delta M_{\max} = 0.4$ and 0.5.

It is necessary to check that the randomization procedure does not affect the basic features of the earthquake sequence, the magnitude–frequency relation being the most important. The magnitude–frequency relations for the OC and for the RCs with $\Delta M_{\max} = 0.3$ and $\Delta M_{\max} = 0.5$ are shown in Fig. 2. The distributions are quite similar and the differences with respect to the OC become relevant only at the largest magnitudes, due to the small number of events. The linearity of the frequency–magnitude relation is preserved even for $\Delta M_{\max}$ as large as 0.5 and the *b*-value does not change significantly, since it is mainly controlled by the small and intermediate magnitude events.

4.2. Predictions based on the original catalog

The application of CN algorithm for the intermediate-term earthquake prediction in central Italy (Fig. 3) is described in detail by Peresan et al. (1999b). Six strong events with $M \geq M_0 = 5.6$ occurred during the considered time interval. In two cases (21 August 1962 and 26 September 1997) two strong earthquakes occurred in the same day and very close in space. Such "coupled" events cannot be distinguished at the time scale characteristic of the algorithm, since CN predictions are performed with a time step of 2 months. These earthquakes will be associated to the same TIP, hence they must be counted just as a single event (i.e. instead of six strong earthquakes, there are just four events to be predicted).

The results of predictions obtained for two different thresholds setting periods are shown in Fig. 4. In the first case the thresholds setting period, referred as *long period*, lasts from 1 January 1954 to 31 December 1998. In the second case, it lasts from 1 January 1954 to 31 December 1985, and it is referred as *short period*. The results of predictions are summarized in the following paragraphs.

For the long thresholds setting period (Fig. 4a), three out of the four strong events are predicted, with the percentage of the total alarm duration $\tau \approx 21\%$. The coupled event ($M = 5.7$ and 6.0), occurred on 26 September 1997, is a failure to predict; hence $\eta = 25\%$ and $\Omega \approx 46\%$. For the short thresholds setting period (Fig. 4b), TIPs occupy about 22% of the total time and precede all the four strong events, hence $\eta = 0$, $\tau \approx$

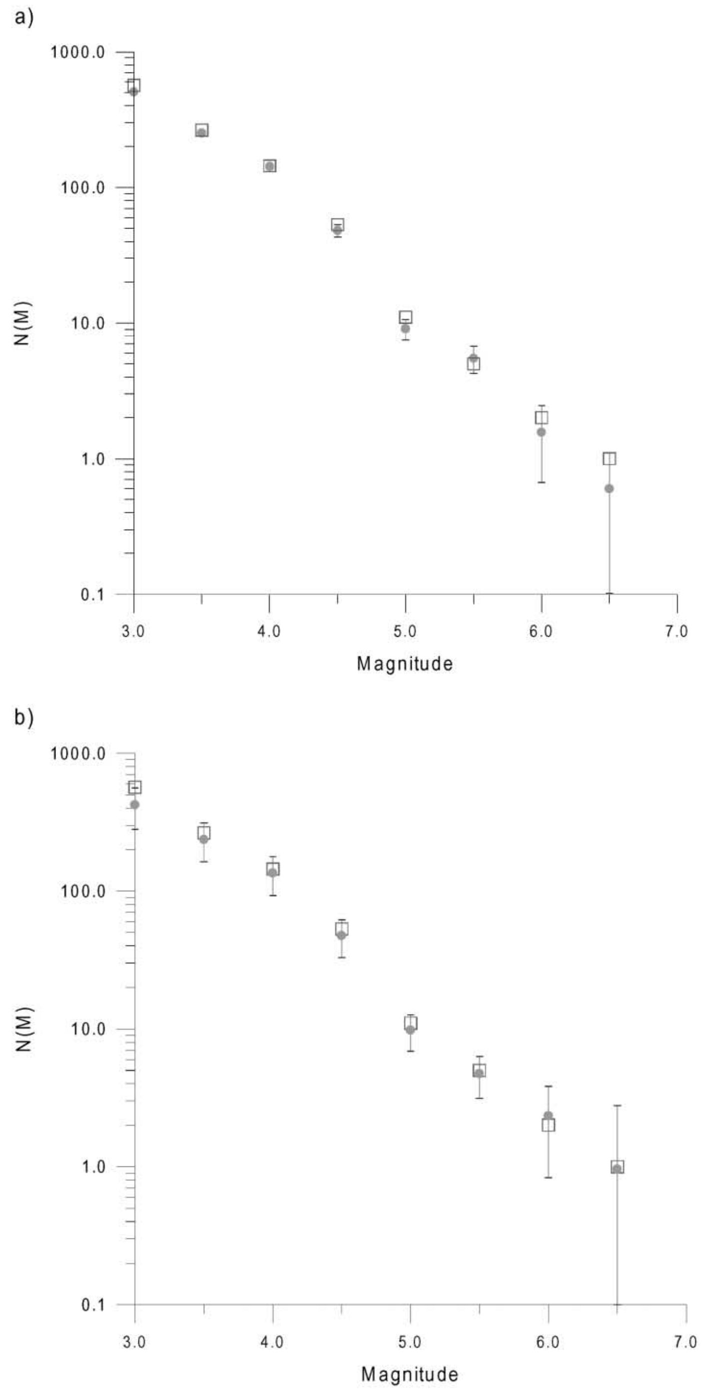

Fig. 2. Distribution of the number of events versus magnitude for the RCs with (a) $\Delta M_{\max} = 0.3$ and (b) $\Delta M_{\max} = 0.5$. For each magnitude interval the average number of events (filled dots) and its S.D. (vertical bars) are given for the RCs, together with the number of events in the OC (open squares).

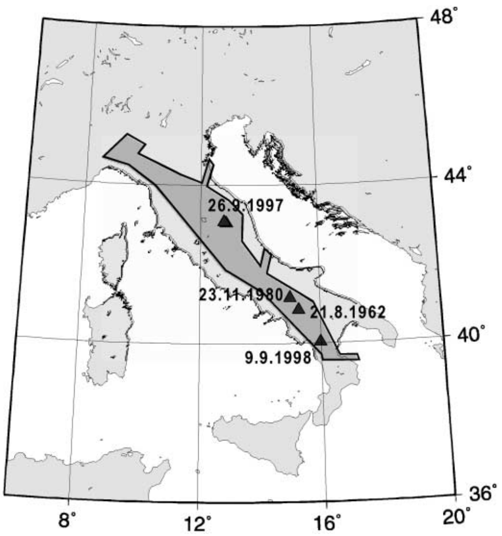

Fig. 3. Region used for the routine application of the algorithm CN in central Italy (Peresan et al., 1999b). The epicentres of the strong events are given together with their occurrence time. Note that the events occurred on 21 August 1962 and 26 September 1997, are "coupled" events (i.e. two strong earthquakes occurred in the same day and close in space).

22% and $\Omega \approx 22\%$. Therefore, predictions associated with the short thresholds setting period seem to provide a better score, despite of the reduced information considered. However, the analysis of the stability of these two results, described in Section 4.3, will show that the long thresholds setting period supplies more stable results.

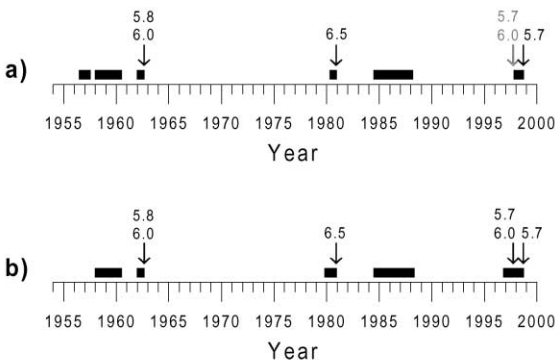

Fig. 4. TIPs obtained with the OC for (a) the long thresholds setting period and (b) the short thresholds setting period. Black boxes indicate the TIPs (periods of alarm). Arrows with a number above indicate the time of occurrence of strong earthquakes and their magnitude; failures to predict are given in gray.

4.3. Predictions based on the randomized catalogs

The algorithm CN is applied to each of the RCs independently, following the standard rules. The threshold M_0 for the selection of the events to be predicted is kept equal to 5.6, the same as for the OC, in order to check the stability of the set of events to be predicted with respect to this threshold.

The results of predictions obtained for 50 RCs—10 for each $\Delta M_{\max}$ from 0.1 to 0.5—are synthetically described by means of the sum of errors $\Omega = \eta + \tau$. The values of Ω versus $\Delta M_{\max}$ are shown in Fig. 5.

With the long thresholds setting period (Fig. 5a), individual results can be comparable or even better than the original one for $\Delta M_{\max}$ up to 0.4; the values of $\langle\Omega\rangle$, averaged for each $\Delta M_{\max}$, are approximately equal to the original value ($\Omega = 46\%$) for $\Delta M_{\max} \leq 0.2$. The exact values of the average errors of prediction, $\langle\tau\rangle$, $\langle\eta\rangle$ and $\langle\eta + \tau\rangle$ (together with its S.D. σ) for the different $\Delta M_{\max}$, are given in Table 1. The original result obtained with the long thresholds setting period appears quite stable with respect to magnitude errors up to ± 0.2.

For the short thresholds setting period (Fig. 5b), one can observe an increasing trend of $\langle\Omega\rangle$, showing that the quality of predictions decreases almost linearly with $\Delta M_{\max}$. In particular, the average values $\langle\Omega\rangle$ are significantly larger than the $\Omega = 22.1\%$ corresponding to the OC and all the results obtained using the RCs appear worse than the original one. Hence, this result appears very sensitive to possible magnitude errors. Its good quality, obtained at the price of stability, seems to indicate some over-fitting to the original data, and casts some doubts about the real predictive capability of CN, when using the short thresholds setting period.

The analysis described earlier allows us to single out the instability of the prediction results related to the insufficient length of the thresholds setting period. In fact, due to the small number of strong events occurred during the short thresholds setting period (only two events), the information provided to the algorithm about the seismic activity preceding the strong events is limited, and hence it strongly depends on the few given cases.

Henceforth, we consider only the long thresholds setting period. For $\Delta M_{\max} = 0.4$ and 0.5, 10 tests permit already to evidence the instability of results; therefore it seems not necessary to investigate further

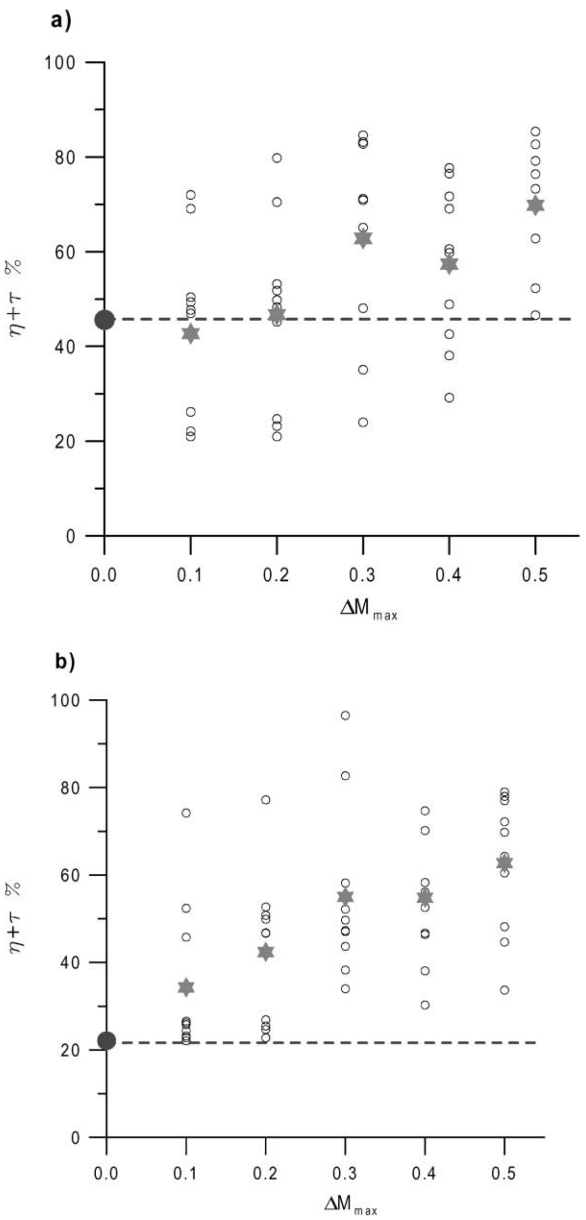

Fig. 5. Diagram showing the dependence of prediction errors $\Omega = \eta + \tau$ on $\Delta M_{\max}$ for (a) the long thresholds setting period and (b) the short thresholds setting period. The circles indicate the $\eta + \tau$ values for the 10 RCs used for each $\Delta M_{\max}$; stars show their average values. The horizontal dashed line and the full dot indicate the $\eta + \tau$ value for the OC. The quantities η and τ are defined in the text.

Table 1
Average errors of prediction for different $\Delta M_{\max}$

$\Delta M_{\max}$	$\langle\tau\rangle$ (%)	$\langle\eta\rangle$ (%)	$\langle\eta + \tau\rangle \pm \sigma$ (%)
0.1	22.8	22.5	42.7 ± 19.1
0.2	24.1	28.8	46.7 ± 19.6
0.3	26.5	40.6	62.8 ± 20.9
0.4	27.1	30.3	57.4 ± 17.0
0.5	28.6	41.2	69.8 ± 12.7

the effects of such large errors. For smaller errors, instead, additional tests are needed, in order to properly evaluate the stability of the results, as well as to improve the significance of the analysis. A comprehensive analysis is then performed for 90 RCs, 30 each for $\Delta M_{\max} = 0.1$, 0.2 and 0.3, respectively. In fact, $\Delta M_{\max} = 0.3$ is a realistic estimate of the upper bound for the error which can affect magnitudes (Båth, 1973; Panza and Calcagnile, 1974; Herak et al., 2001) and it corresponds to the value of $\Delta M_{\max}$ for which predictions begin to be unstable (Fig. 5a).

The stability of the results is evaluated by means of the error diagrams (Molchan et al., 1990), compiled for the results obtained with the OC and the RCs (Fig. 6). Each point in the (η, τ) plane corresponds to the prediction obtained for a given catalog; the diagonal line defined by the equation $\Omega = \eta + \tau = 100\%$ corresponds to the results of a random guess. The clustering of points indicates the stability of predictions, while the increasing distance from the diagonal line indicates the increasing quality of the predictions. Fig. 6 shows that, for $\Delta M_{\max} \leq 0.2$, the results are quite well clustered around the one obtained with the OC, while for $\Delta M_{\max} \leq 0.3$ they appear much more scattered. The error τ, indicating the percentage of time occupied by alarms, does not vary significantly with respect to the original predictions. Therefore, the changes in the quality of the results are mainly due to a larger percentage of failures to predict η, which is strictly related to the changes in the number of events to be predicted. This aspect emerges quite clearly from Table 2, showing the average difference between the CN results obtained using the OC and those obtained using the RCs: $\langle\Delta\tau\rangle = \langle\tau\rangle - \tau_{\mathrm{O}}$ and $\langle\Delta\eta\rangle = \langle\eta\rangle - \eta_{\mathrm{O}}$, where τ_{O} and η_{O} are the prediction errors for the OC (Fig. 6). The average variation of the number of strong events N_{SE} has been evaluated by means of the relation: $\langle\Delta N_{\mathrm{SE}}\rangle = \langle|N_{\mathrm{R}} - N_{\mathrm{O}}|/N_{\mathrm{O}}\rangle$, where N_{O} and

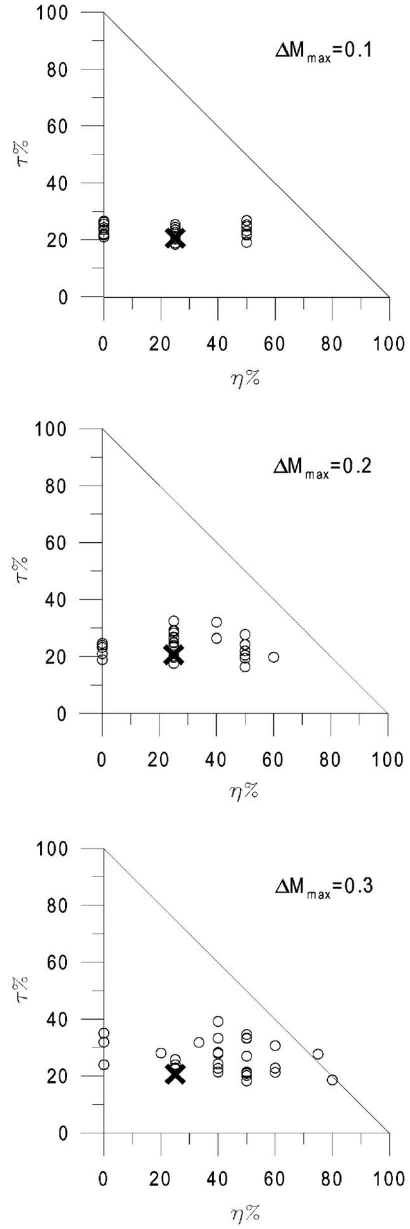

Fig. 6. Error diagrams for the results of TIPs diagnosis using the OC (bold cross) and the RCs (circles) with long thresholds setting period. The diagonal line corresponds to the results of a random guess. Thirty tests have been performed for each ΔM_{max}.

N_R are the numbers of events to be predicted (with $M \geq 5.6$) in the OC and in the RCs, respectively; for $\Delta M_{max} = 0.3$ both $\langle \Delta N_{SE} \rangle$ and $\langle \Delta\eta \rangle$ increase significantly.

Table 2
Average difference between the results of CN obtained using the OC and those obtained using the RCs

ΔM_{max}	$\langle \Delta\tau \rangle$ (%)	$\langle \Delta\eta \rangle$ (%)	$\langle \Delta(\eta + \tau) \rangle$ (%)	$\langle \Delta N_{SE} \rangle$ (%)
0.1	2.2	−2.5	−0.3	0.0
0.2	3.5	3.8	7.3	2.5
0.3	5.9	15.6	21.5	13.4

$\langle \Delta\tau \rangle$, $\langle \Delta\eta \rangle$: average variation of prediction errors for the RCs; $\langle \Delta N_{SE} \rangle = \langle |N_R - N_O|/N_O \rangle$: average variation of the number of strong events; N_O: number of events to be predicted in the OC; N_R: number of events to be predicted in the RC.

A list of the earthquakes, ordered by decreasing magnitude, with $M \geq 5.3$ in the OC, occurred in central Italy (Fig. 3) during the period 1950–1999, is provided in Table 3. This table contains information about all the events whose randomized magnitude may exceed the threshold $M_0 = 5.6$ for $\Delta M_{max} = 0.3$. The percentage of times each earthquake turns out to be a strong event, N_{SE}, and the percentage of times it is predicted (N_P) are provided as well, considering 30 RCs. The table shows that the earthquakes with original magnitude less than 5.6, sporadically becoming strong events, are never predicted. This explains the drastic increase of the error η for $\Delta M_{max} = 0.3$, and at the same time indicates that the randomization does not introduce spurious alarming patterns, as it clearly appears from the analysis of the stability of TIPs identification.

To evaluate the stability of predictions we have analyzed also the variation of TIPs. Considering a set of predictions made for the same time interval, the quantity $\Theta(t)$ has been defined as the percentage of cases where the instant t is identified as a TIP.

Table 3
List of earthquakes with $M \geq 5.3$, central Italy 1950–1999

Event date	M	N_{SE} (%)	N_P (%)
23 November 1980	6.5	100.0	66.7
21 August 1962[a]	5.8/6.0	100.0	93.3
26 September.1997[a]	5.7/6.0	100.0	40.0
9 September 1998	5.7	83.3	56.0
19 September 1979	5.5	23.3	0.0
5 May 1990	5.5	12.0	0.0
7 May 1984	5.4	0.0	0.0

[a] "Coupled" events, occurred in the same day and very close in space. The magnitudes of both the strong earthquakes are provided.

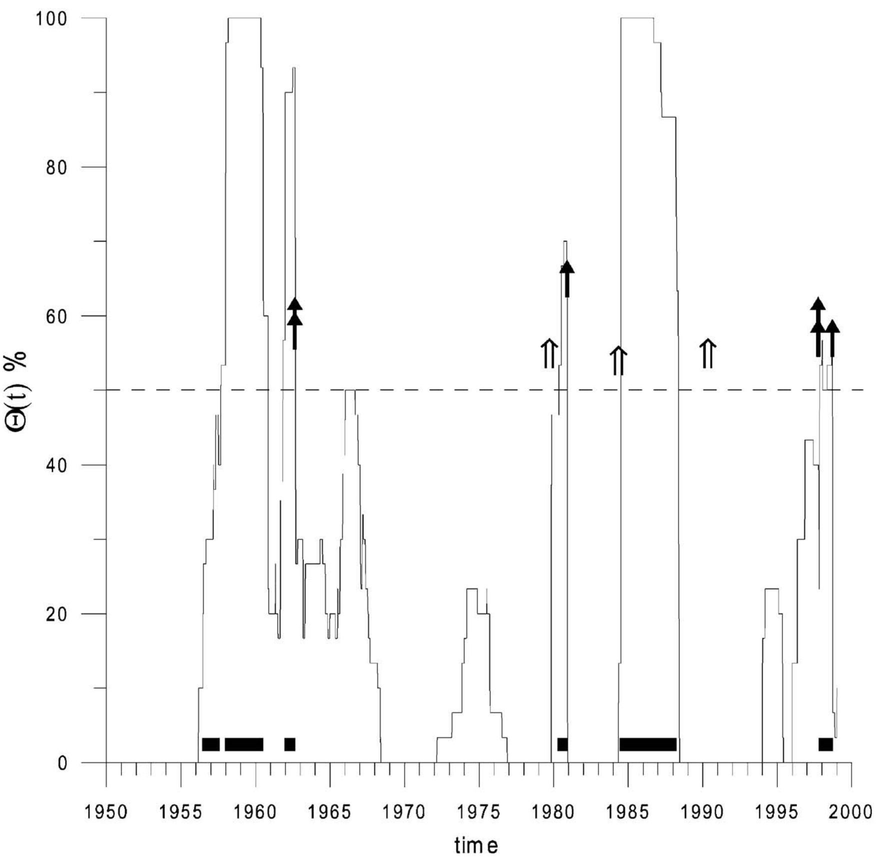

Fig. 7. The percentage $\Theta(t)$ is the number of tests for which the time (t) belongs to a TIP. Black boxes represent the TIPs declared using the OC. Black arrows indicate the time of occurrence of strong earthquakes ($M \geq M_0 = 5.6$) in the OC. Grey open arrows indicate additional strong earthquakes sporadically appearing in the RCs. The distance of the arrows from the dashed line is proportional to the magnitude reported in the OC. Thirty tests have been performed with $\Delta M_{\max} = 0.3$.

Fig. 7 shows the function $\Theta(t)$ based on the results of predictions for the 30 RCs with $\Delta M_{\max} = 0.3$.

All the original TIPs appear to be very stable; moreover, TIP is never declared during considerable part of the time. This confirms the conclusion about the high stability of the results.

5. Discussion and conclusions

The stability of the intermediate-term predictions with respect to random errors in magnitudes has been evaluated considering as an example the CN prediction for central Italy. The algorithm has been applied, following the standard rules, to a set of catalogs with magnitudes randomly modified (RCs) within the range of the assumed errors, and the outcomes of these predictions have been compared with the results obtained with the OC. Our analysis shows that the results of prediction remain stable for $\Delta M_{\max} < 0.3$. The quality of predictions seems to be mainly controlled by the percentage of failures to predict, which depends on the changes in the number of strong earthquakes ($M \geq M_0$), almost negligible for $\Delta M_{\max} \leq 0.2$. The strong events generated by the randomization are never predicted, thus increasing the percentage of failures to predict.

The procedure used here for magnitude randomization has been defined on the basis of quite rough and sketchy arguments. This study, however, is not aimed to provide neither the optimal randomization procedure nor the best definition of random magnitude errors and certainly, the appropriate construction of the optimal model for such errors represents an open problem.

Prediction algorithms have generally a set of fitting parameters that, in the case of CN algorithm, correspond to the thresholds for normalization and discretization of functions. These parameters are fixed by the retrospective analysis of seismicity during the thresholds setting period; once they are assigned from the analysis of past seismicity the algorithm is applied for prediction, using such fixed parameters. The randomization procedure introduced in this paper can help both to evaluate the stability of the algorithm and to prevent data over-fitting. The tests performed with the RCs show that, with a short thresholds setting period, the average quality of results decreases linearly for increasing magnitude error, while with a longer thresholds setting period it appears to be constant, at least for $\Delta M_{\max} < 0.3$. This indicates that, in order to guarantee a certain stability of the results, the thresholds setting period must be long enough to include a significant sample of dangerous and non-dangerous intervals of time, otherwise the assigned parameters of the algorithm will strongly depend on the few given cases. This would lead to an excessive sensibility to possible data errors and hence to worst prediction results.

Therefore, from now onward, the application of the algorithm CN in Italy will be performed using the parameters fixed with the analysis of the OC with the long thresholds setting period. In this case, the results should be robust at least for magnitude errors lower than ± 0.3, with an expected score around $\Omega = 55\%$. This value of Ω is in good agreement with the average performance of CN in 22 regions of the world (Rotwain and Novikova, 1999). The results of routine predictions for the central Italy region (Fig. 3), updated to 1 September 2001, indicate a TIP, lasting from November 2000 up to 1 September 2002, both considering the short and the long thresholds setting period.

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