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Analysis of precursory seismicity patterns in Zagros (Iran) by CN algorithm

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Abstract: This study illustrates the application of the CN algorithm for the analysis of precursory seismicity patterns in the Zagros region (Iran), an area characterized by a complex seismotectonic setting and by remarkable seismic activity. CN is a formally defined and widely tested algorithm for intermediate-term middle-range earthquake prediction, based on the analysis of routinely compiled earthquake catalogs. To allow its application, the global and regional catalogs available for the territory of Iran have been analyzed so as to compile a data set sufficiently complete and homogeneous over a time span of about 3 decades, as required for CN application. A number of tests have been performed with respect to changes in the input catalogs, assuming different magnitude completeness levels as well as considering different magnitude thresholds for the selection of target earthquakes. Different variants of the regionalization have been outlined according to the seismotectonic model, and it was concluded that precursory seismicity patterns for the largest events need to be researched in the whole Zagros tectonic domain. Accordingly, an experiment was set up aimed at validation of intermediate-term middle-range prediction of earthquakes with magnitude $M \geq 6.0$ in the Zagros region. Starting in March 2012, CN prediction results have been routinely updated based on the events with $M \geq M_c = 4.0$ as they are reported in the International Seismological Centre catalog.

Key words: CN algorithm, Zagros, Iran, earthquake prediction, seismicity patterns

1. Introduction

The space and time constraints about future earthquake occurrences, including those provided by earthquake prediction experiments, are of primary interest in seismic risk mitigation (Jordan et al., 2011; Peresan et al., 2012). Different preparedness actions can be undertaken depending on the uncertainties associated with the issued alerts; possible actions may range from long-term land planning and building codes to time-dependent seismic hazard assessment, and from retrofitting of critical structures to increased emergency preparedness and evacuation plans (Keilis-Borok and Primakov, 1997).

An increasing number of studies show that patterns of occurrence of small and moderate earthquakes may bring relevant information on the location and time of occurrence of future major earthquakes (Keilis-Borok and Kossobokov, 1990; Jackson and Kagan, 1999; Kossobokov et al., 1999; Kagan and Jackson, 2000; Rhoades and Evison, 2004, 2005; Tiampo et al., 2008). Amongst the different proposed methods, the CN algorithm (Keilis-Borok and Rotwain, 1990) is considered in this study, since it is fully formalized and has been already submitted to a rigorous validation process. The CN algorithm is an intermediate-term middle-range earthquake prediction method that identifies the time of increased probability (TIP) for the occurrence of a strong earthquake by searching for multiple precursory seismicity patterns. The seismicity patterns are quantified by means of a specific set of functions, namely the "functions of seismic flow", defined by a detailed retrospective analysis of seismicity in the California-Nevada region. This method has been undergoing real-time prospective testing for more than 20 years in several regions worldwide (Rotwain and Novikova, 1999; Peresan et al., 2005, Panza et al., 2011) and the results show that CN could be used as a statistically significant earthquake forecasting method.

In this study the application of the CN algorithm to the territory of Iran is explored, focusing on the Zagros region (W Iran). The Zagros mountain belt connects to the North and East Anatolian faults in the east of Turkey

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and runs to the Makran subduction zone in the south of Iran. The Zagros accommodates part of the convergence between Arabia and Eurasia (Tatar et al., 2002) and is a seismically active fold and thrust belt. Zagros is the most seismically active province in Iran (Tavakoli and Ashtiany, 1999), which permits the attempt to apply the CN method.

Various formalized earthquake prediction methods, like the CN algorithm, are based on the analysis of earthquake catalogs, which still remain the most objective and long-term record of seismic activity, but which require a preliminary assessment of their completeness and the removal of duplicates and other possible errors (Shebalin, 1992). In this study, different global catalogs (those of the National Earthquake Information Center [NEIC] and the International Seismological Centre [ISC]) plus regional data sets (those of the International Institute of Earthquake Engineering and Seismology [IIEES] and Institute of Geophysics, Tehran University [IGTU]) were analyzed. As described in Section 2, the ISC catalog turns out to be the preferable data set in terms of space-time span completeness and it was selected for the CN algorithm application in the Zagros area.

2. Data

Within a selected region, the application of the CN algorithm requires the definition of 1) magnitude of target earthquakes (M_0), 2) magnitude thresholds (m_1, m_2, m_3) to be used in the normalization of the functions defined in the CN (average annual number of events with magnitude equal to or more than these thresholds in the selected area must be equal to or more than the constant numbers), and 3) thresholds for the discretization of the CN functions. Once Step 1 is performed, the thresholds in Steps 2 and 3 are automatically set based on past seismicity during the threshold-setting period (Peresan et al., 2002). If the condition $m_3 > m_2 > m_1 \geq M_c$ is satisfied, assuring that all functions are computed for earthquakes above the completeness threshold M_c, the monitoring of seismicity can start. Owing to the normalization of its functions, CN can be applied to regions with a different seismicity level without any adjustment (data fitting) of the functions and parameters (Peresan et al., 2005). With the CN algorithm, the monitoring of seismicity is performed every 2 months; thus, the availability of a catalog updated with a time delay not exceeding a couple of weeks is required.

The catalogs available for Iranian territory are regional (IIEES and IGTU) and global (ISC and NEIC). The IIEES catalog starts in 1900 and the data from before 2004 were compiled from globally accessible catalogs (mainly ISC); after 2004, the IIEES catalog relies upon the IIEES broadband seismic network and the predominant magnitude measure is local magnitude ML. The IGTU catalog is accessible from 2006 for the whole of Iran and it supplies Mn (Nuttli, 1973) magnitude. The ISC provides a large number of magnitude types that can be divided into 3 main groups: 1) teleseismic, 2) complementary magnitude, and 3) local magnitude. Within the Iranian territory, the magnitude Ms (surface wave magnitude) is reported for most of the events (53%), whereas ML is provided for about one-third of them (32%). Three different versions of the earthquake bulletins are supplied by the ISC and are tested for CN application in Zagros, namely the ISC CD-ROM, the website 'Reviewed ISC Bulletin' (ISC-Rev), and the website 'ISC Bulletin' (ISC-Bul). ISC-Bul is the most complete and timely data set. The global NEIC catalog for this region supplies magnitudes in 6 different magnitude scales, including moment magnitude Mw, surface wave magnitude Ms, body wave magnitude mb, and local magnitude ML. Within the Iranian territory most of the earthquakes are measured in the mb scale (90%), followed by the ML, Ms, and Mw scales, in that order. In view of the large variety of magnitude types, for our purpose, we use the maximum magnitude. The operating magnitude, chosen for each event, is the maximum of the selected magnitudes given in the ISC catalog.

The input catalog for the CN algorithm, as for other intermediate-term middle-range prediction algorithms (Peresan et al., 2011), must be, as far as possible, homogeneous and sufficiently extended in space and time. 'Homogeneous' means that earthquake size estimates (i.e. their magnitudes) stay consistent over time and the required completeness level, M_c, is preserved in the whole time window of the CN application. Once the study area is defined, the assessment of the catalog homogeneity and its variation with time can be based on the Gutenberg–Richter (G-R) law (Peresan et al., 1999b). For the ISC catalog, it is possible to identify 3 intervals characterized by different homogeneities, namely 1950–1975, 1975–1995, and 1995–2011 (Figure 1a). The G-R graphs for the 3 periods show that in the period of 1975–1995, magnitude of completeness M_c is above 4.0 (close to 4.5), while in the period of 1995–2011, M_c is about 4.0 (Figure 1b).

Similar to ISC, analysis of the IIEES catalog shows that in the period of 1975–1995, M_c is close to 4.5, while in the period of 1995–2011, $M_c \approx 4.0$. The NEIC catalog shows that in the period of 1975–1995, M_c appears to be close to 4.7, while in the period of 1995–2011, $M_c \approx 4.5$. The G-R graph and the temporal evolution of the semiannual number of earthquakes above different magnitude thresholds in the IGTU catalog shows that since 2006 the completeness improved to $M_c \approx 2.5$. Such a short period is not sufficient for the purposes of CN and other similar algorithms; nevertheless, a $M_c \approx 2.5$ starting in 2006 may allow improving (after 2030) of the quality of current predictions, and also on account of the ongoing development of the IIEES network. At the end of

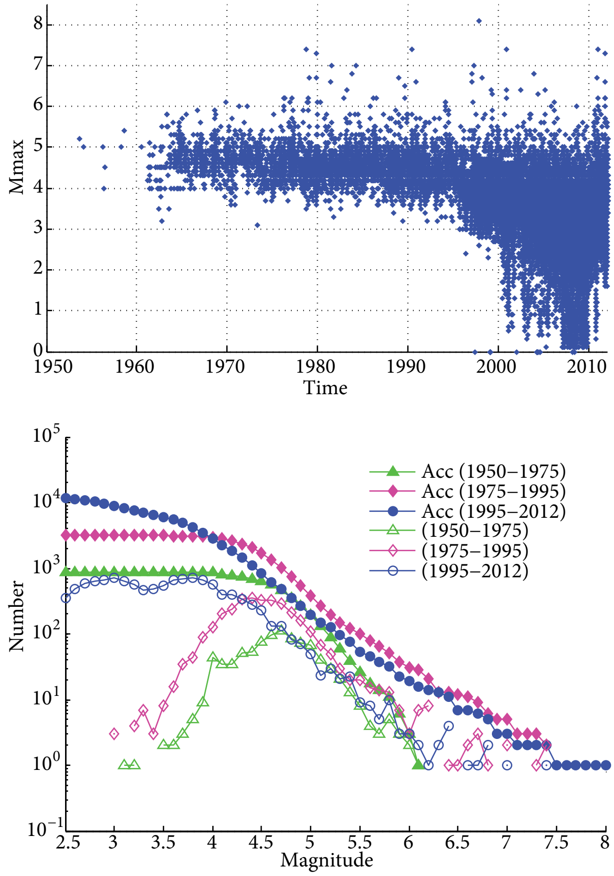

Figure 1. Exploratory analysis of the ISC catalog: a) magnitude (Mmax) versus origin time, b) frequency–magnitude relation (empty markers = noncumulative, filled markers = cumulative) of earthquakes for the selected periods: 1900–1975 (triangles), 1975–1995 (diamonds), and 1995–2011 (circles).

September 2011, 24 seismic stations were active, meaning that they were online and information was continuously being transmitted by satellite to the IIEES; out of these 24 stations, 9 are located in the Zagros region. By the completion of the broadband seismic network, 42 stations will record seismic activity of Zagros and thus the M_c for this region will be about 1.5.

Results from the analysis of the 4 mentioned catalogs were considered for the selection of the most adequate data set for CN application. Between the global catalogs (ISC and NEIC), the completeness and therefore the quality of the ISC catalogs are higher than that of NEIC catalog. Amongst the IIEES and IGTU regional data sets, IIEES turned out to be preferable, since it covers a sufficient time span. To choose between IIEES and ISC we compared their homogeneity by means of normalized G-R graphs (Figure 2). Three periods were identified: the first (1975–1995) and second (1995–2004) are characterized by a comparable completeness, whereas the last period (2004–2011) is defined by the installation of the IIEES broadband network. According to Figure 2, the G-R curves for different periods obtained from the ISC catalog are in good agreement, particularly in the magnitude range of [4.0; 5.5]. On the other hand, the spacing between the different G-R curves obtained from the IIEES catalog evidence some general level changes in seismic activity, which suggest a certain heterogeneity of the catalog. Based on the above considerations, the ISC catalog appeared preferable for CN application in Iran.

3. Regionalization

For the CN algorithm, seismotectonic regionalization is important a priori information necessary to obtain reliable results and to reduce the space-time uncertainty of predictions (Peresan et al., 1999a). The earthquake catalogs for Iran show that most of the seismic activity is concentrated in the Zagros region, where previous seismic hazard analyses led to the identification of several different seismotectonic regions (Stoecklin, 1968; Takin, 1972; Berberian, 1976; Nowroozi, 1976; Berberian and King, 1981; Mirzaei and Chen, 1999; Tavakoli and Ghafori-Ashtiany, 1999).

The definition of regions for prediction purposes must correspond, on one hand, to areas as small as possible to decrease the space uncertainty, but on the other hand, these regions should be large enough to guarantee sufficient statistics for the earthquakes involved in the analysis and must include the zones where the strong earthquakes and their possible precursory patterns are likely to occur (Peresan et al., 1999a). According to previous studies, the area of investigation for a CN application is selected taking into account the spatial distribution of seismicity and the geometry of fault systems and must satisfy 3 general rules: 1) its linear dimensions must be not lower than 5L–10L, where L = L(M_0), the rupture linear size of the target earthquake (estimated, for example, by using the empirical relation proposed by Wells and Coppersmith [1994]); 2) the border of the area must correspond, as much as possible, to minima in the seismicity, to minimize border effects; and 3) on average, at least 3 events with magnitude over the completeness threshold M_c should occur inside the area of investigation each year (i.e. the yearly average number of events with $M \geq M_c$ must be > 3). Rule 1 guarantees that the linear size of the events with $M < M_0$ is negligible with respect to the size of the study area and thus satisfies the self-similarity condition for the small and moderate events expressed by the log-linearity of the frequency-magnitude relation, in agreement with the multiscale seismicity model (Molchan et al., 1997). In such a way, the CN algorithm makes use of the information carried by small and moderate earthquakes, statistically characterized by the G-R law, to predict the strong earthquakes that do not fit it and hence escape the

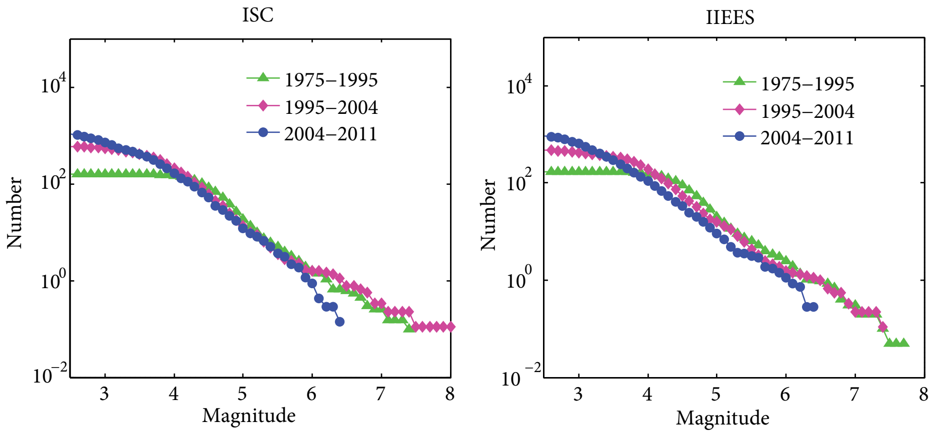

Figure 2. Normalized cumulative G-R relation for the selected periods: 1975–1995 (triangles), 1995–2004 (diamonds), and 2004–2011 (circles). The IIEES catalog is on the right and the ISC catalog is on the left.

unpredictability often associated with the self-organized criticality paradigm (e.g., Bak et al., 2002). Rule 3 ensures that the detection level controls, to some extent, the time–space uncertainty of prediction (Keilis-Borok, 1996), and thus the possibility of reducing the spatial uncertainty is controlled by the difficulty of keeping a high level of detection due to unavoidable logistic problems (Peresan et al., 2005).

For the first application of the CN algorithm in Iran, an area was identified that encompasses the available seismotectonic zonations of the Zagros area (Figure 3). Figure 3 shows 2 different zonations that have been proposed for Zagros (Nowroozi, 1976; Tavakoli, 1999), along with the recent seismicity of Iran (ISC catalog, 1900–2011). For the CN application, a wider area, whose borders are defined by a minimum in the seismicity, was chosen to take into account all the events in the vicinity of Zagros. In order to possibly reduce the space–time uncertainty of the predictions by taking into account the difference in tectonic style (shortening) in the northern and southern

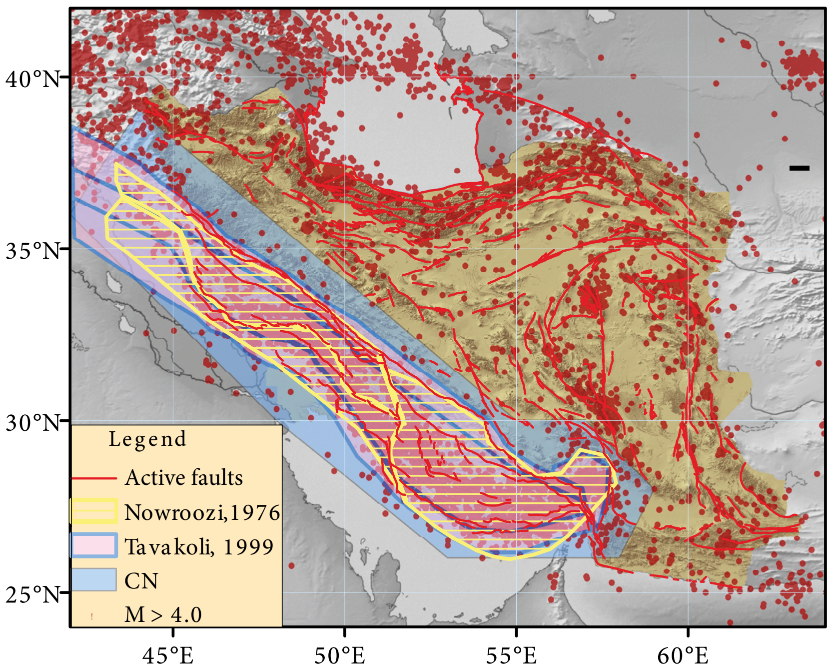

Figure 3. Regionalization in Zagros used for the application of the CN algorithm, along with the seismotectonic zones defined for the seismic hazard analysis and active faults (Hessami et al., 2003). Red dots indicate the epicenters of earthquakes with M > 4 that occurred in the period 1900–2011, as reported in the ISC catalog.

part of Zagros, 2 partially overlapping subregions were defined based on the seismotectonic zoning. In the northern region, the seismicity level is relatively lower than in the southern region (Figure 4). The overlapping part of the 2 regions is related to strike-slip faults, such as the Kazerun fault, and it is considered to be a transition zone between North Zagros and South Zagros as outlined for the CN application. Naturally, when applying CN to the 2 subregions, Steps 1, 2, and 3 as described in Section 2 were applied.

4. The CN algorithm in Zagros

The CN algorithm application in the Zagros region was carried out via a set of retrospective experiments that aimed to identify an appropriate configuration of the basic elements in the procedure, namely the boundaries of the region and the magnitude thresholds M_0 and M_c, as well as the most appropriate input data set. These sensitivity tests were essential to set up a systematic real-time analysis of seismicity patterns, which may provide sufficiently stable and satisfactory prediction results in prospective testing. As mentioned in Section 2, 3 different variants of the ISC bulletins were tested, namely ISC-Rev, ISC-Bul, and ISC-CD-ROM. For each catalog variant, 2 procedures were followed to remove duplicates (i.e. 2 records of the same earthquake reported in the catalog), referred to as the standard and the manual procedures by Shebalin (1992). Thus, the stability of the CN results was tested against 6 variants of the input catalog. Since the CN algorithm makes use of declustered catalogs, aftershocks were removed from each catalog following the criteria proposed by Keilis-Borok et al. (1980).

The threshold for the selection of strong events, M_0, was chosen to correspond to the minimum number of events in the histogram versus magnitude (Peresan et al., 2005), and 3 values of M_0 (6.0, 6.1, and 6.2) satisfied this condition within the CN region shown in Figure 3. According to the catalog analysis, M_c is about 4.0; however, in order to test the sensitivity of the results on the choice of value for this parameter, we considered 4.5, as well.

Thus, in the parametric experiments of the CN application to the Zagros region, different values for threshold (M_0) and completeness (M_c) magnitudes were considered and were tested with respect to several catalog variants. The results obtained from the different tests are summarized in Figures 5 and 6 and in Table 1.

In Figure 5, the results of CN are reported in the so-called error diagram (Molchan et al., 1990). 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 the parametric tests, while the increasing distance from the diagonal line indicates the increasing quality of the predictions. Since the results obtained with the ISC-Rev catalog are the closest to the diagonal, we can discard this catalog in our future applications of CN. The remaining catalogs, ISC-CD-

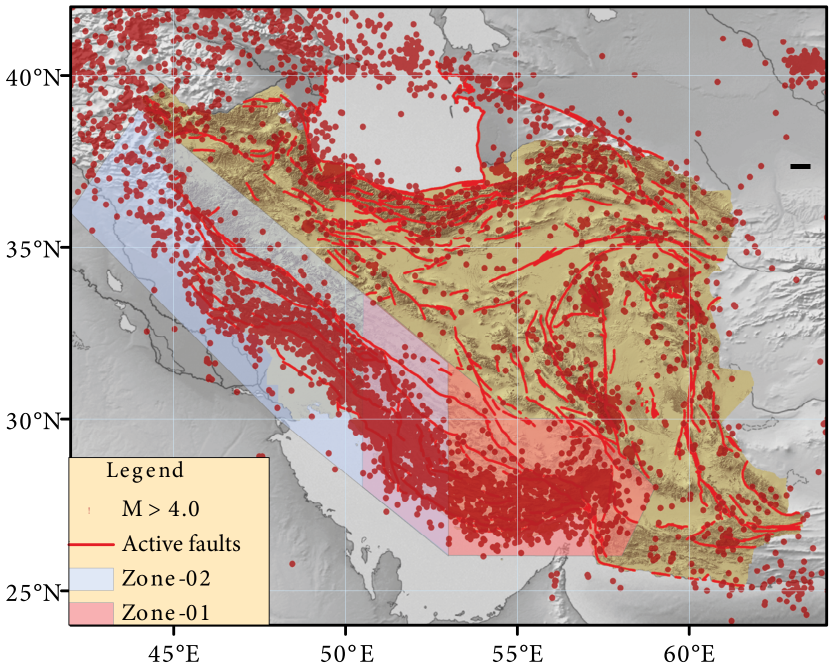

Figure 4. Second variant of the regionalization for the CN application to the Zagros area, along with active faults (Hessami et al., 2003) and recorded seismicity. Two partially overlapping zones are considered.

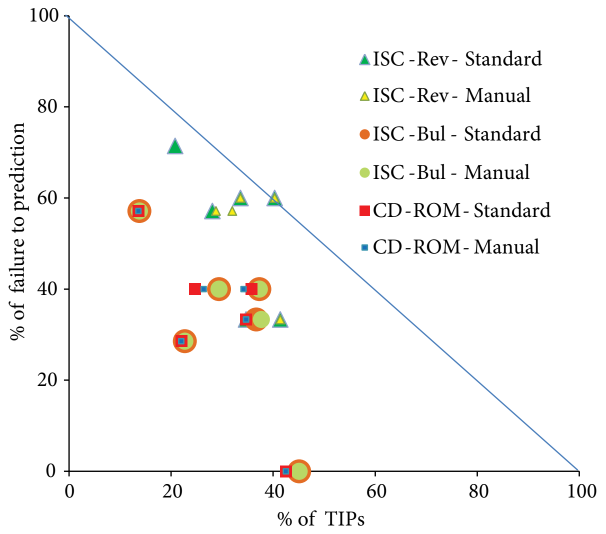

Figure 5. Error diagram (n-τ diagram) of the percentage of failures to predict (n) versus total TIPs (τ) for the results obtained in Zagros, considering the different ISC Bulletins, completeness (M_c), target event thresholds (M_0), and magnitude thresholds.

ROM and ISC-Bul, provide very similar results and we preferred ISC-Bul for our purposes since it is updated in a timely manner.

In Figure 6, the same results from the CN testing, obtained for the ISC-CD-ROM and ISC-Bul catalogs, are illustrated, focusing on the distinct magnitude thresholds. Different symbols corresponding to the magnitude thresholds were used for the selection of target earthquakes, namely M_0 = 6.0, 6.1, and 6.2. The color code

Table 1. Results obtained with the CN algorithm in Zagros, Iran, using the ISC-Bul catalog with different completeness (M_c), target event (M_0), and magnitude thresholds.

M_0	M_c	Number of target events	Failure to predict	TIP %
6.0	4.0	7	2	22.70
6.0	4.5	7	4	13.80
6.1	4.0	5	2	37.30
6.1	4.5	5	2	29.40
6.2	4.0	3	0	45.10
6.2	4.5	3	1	36.70

defines the value of M_c (red for M_c = 4 and blue for M_c = 4.5). It can be seen that the result for M_0 = 6.1 is the closest to the diagonal line; therefore, this case was omitted in the next steps of the analysis. Thus, we were left with M_0 = 6.0 and M_0 = 6.2. The use of M_0 = 6.2 provided good results, but the statistics were naturally lower than those for M_0 = 6.0 and the use of M_c = 4.5, in general, decreased the quality of the related results (higher percentage of failures). Since the case corresponding to M_c = 4 had better quality than the others (Table 1), the case with M_0 = 6.0 and M_c = 4.0 seemed preferable as a benchmark.

In the second experiment, the possibility of reducing the space uncertainty of predictions was explored by dividing the Zagros region into 2 main subregions (zone-01 and zone-02), eventually including or not including the transition zone (zone-tr). In this variant of the regionalization (Figure 4), the thresholds M_0 = 6.0 and M_c = 4.0 and the ISC-Bul catalog were used. Figure 7 shows

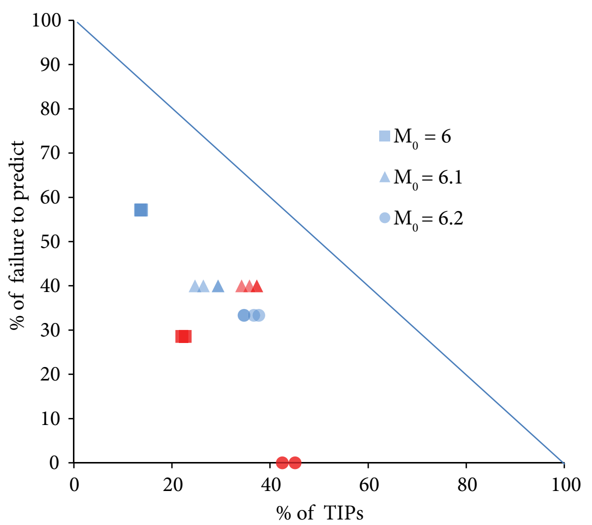

Figure 6. Error diagram obtained for the prediction results sorted by magnitude threshold M_0 (square for M_0 = 6.0, triangle for M_0 = 6.1, and circle for M_0 = 6.2) and by completeness magnitude M_c (red for M_c = 4 and blue for M_c = 4.5).

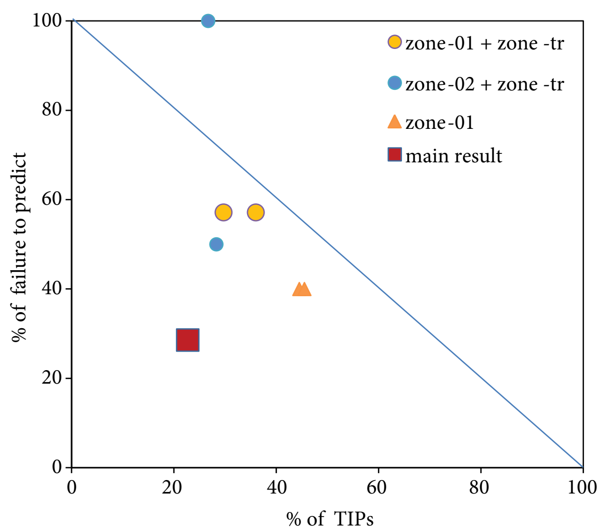

Figure 7. Error diagram pertinent to the regionalization shown in Figure 4, compared with the benchmark result (main result), i.e. the preferred result of the first experiment carried out with the regionalization shown in Figure 3.

the results of this experiment compared with those of the benchmark experiment; the diagram clearly indicates that decreasing the area of monitoring had a negative effect and shifted the results closer to the random case.

A forward prediction was conducted based on all of the above tests of the CN algorithm in the Zagros region analyzed retrospectively from 1979 to 1999 and since June 2000. The real-time earthquake prediction started in March 2012. The predictions are routinely updated every 2 months using ISC-Bul. Since the beginning of the real-time earthquake prediction, no strong earthquake has occurred within the Zagros area and the CN algorithm declared no alarms in this period.

Accordingly, the result of the updated catalog of ISC-Bul (up to November 2012 in this paper) that is used in the CN application is shown in Figure 8. The last declared alarm goes from May 2010 to January 2011 and after that there is no alarm until January 2013.

Evaluation of the performance of the CN algorithm in 22 regions of the world (Rotwain and Novikova, 1999) shows that the percentage of time occupied by alarms is 26% and 11 out of 24 predicted earthquakes (46%) did occur. For the Zagros region, the main result shows that 22% of the total time is occupied by alarms and 5 out of 7 predicted earthquakes (71%) did occur. Although these results show improvement, they still have some limitations, such as alarm times. In Table 2, we consider a 1-year period for alarms. According to the results, alarms will occupy about 11 years. Because there are only 4 years with strong events, we can expect that at least 7 TIPs will correspond to false alarms. Consequently, if we try to evaluate the accuracy in recognition of nondangerous years, we ascertain that it is about 75% (7 out of 25 years are misidentified as dangerous), and then 80% seems a reasonable measure of CN performance. From Table 2 it is possible to see that only 4 of the 11 predictions of an incoming earthquake are correct; therefore, the probability (the ratio of true alarms to total alarms) that a TIP will include an earthquake can be estimated at around 36%. This percentage increases to about 95% when the conditional probability for predictions of no earthquake is considered (21 successes out of 22 forecasts). In fact, prediction of no earthquakes is the strong point of the CN algorithm and if we consider 2-month periods, this advantage increases such that the conditional probability for prediction of no earthquakes would be 98.75%, as seen in Table 3.

5. Conclusion

The first application of the CN algorithm to the Zagros area (Iran) required a preliminary investigation of the different catalogs available at regional and global scales. The ISC data were selected from among them because of their better completeness and homogeneity. Three different variants of the ISC bulletins (CD-ROM, Reviewed, and Bulletin) were tested by the CN algorithm with different magnitudes for the target events (M_0) and different magnitudes of completeness (M_c). The influence of the regionalization on the results of the CN algorithm was analyzed, as well, and showed that decreasing the area of monitoring has a negative effect on the quality of the results.

The performed experiments support the setting up of a system for CN real-time testing of precursory seismicity

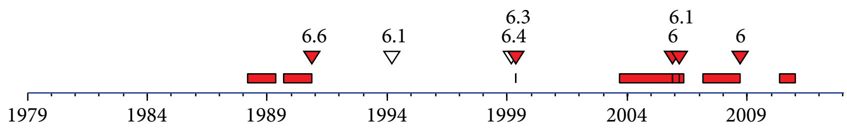

Figure 8. Diagrams of TIPs: boxes represent periods of alarm, while each numbered triangle indicates the occurrence of a strong event ($M \geq M_0$) together with its magnitude. The time interval considered was 1979 to June 2012. Filled triangles represent predicted events and empty triangles represent failures.

Table 2. Contingency table for the CN algorithm in Zagros, with a yearly base rate of earthquake prediction.

	Prediction of earthquake	Prediction of no earthquake	Total	Accuracy of prediction
Years with earthquake	4	1	5	80%
Years with no earthquake	7	21	28	75%
Total	11	22	33	
Conditional probability of predictions	36.4%	95.45%		

Table 3. Contingency table for the CN algorithm in Zagros with a 2-month base rate of earthquake prediction.

	Prediction of earthquake	Prediction of no earthquake	Total	Accuracy of prediction
Two months with earthquake	5	2	7	71.43%
Two months with no earthquake	39	158	197	80.20%
Total	44	160	204	
Conditional probability of predictions	11.36%	98.75%		

patterns in the Zagros region. According to the obtained results, the region shown in Figure 3 will be considered for the prediction of earthquakes with magnitude $M \geq M_0 = 6.0$, based on the information carried by earthquakes with magnitude $M_c = 4.0$ reported in the ISC-Bul catalog. Prospective testing is envisioned, with a regular update of results every 2 months, in order to assess the predictive capability of the proposed CN application.

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References

Bak P, Christensen K, Danon L, Scanlon T (2002). Unified scaling law for earthquakes. Phys Rev Lett 88: 178501–178504.

Berberian M (1976). Contribution to the Seismotectonics of Iran (Part II). Report No. 39. Tehran: Geological Survey of Iran.

Berberian M, King GC (1981). Towards a palaeogeography and tectonics evolution of Iran. Can J Earth Sci 18: 210–265.

Hessami K, Jamali F, Tabassi F (2003). Major Active Faults of Iran [map]. Tehran: International Institute of Earthquake Engineering and Seismology.

Jackson DD, Kagan YY (1999). Testable earthquake forecasts for 1999. Seismol Res Lett 70: 393–403.

Jordan T, Chen Y, Gasparini P, Madariaga R, Main I, Marzocchi W, Papadopoulos G, Sobolev G, Yamaoka K, Zschau J (2011). Operational earthquake forecasting: state of knowledge and guidelines for utilization. Ann Geophys 54: 316–391.

Kagan YY, Jackson DD (2000). Probabilistic forecasting of earthquakes. Geophys J Int 143: 438–453.

Keilis-Borok VI (1996). Intermediate term earthquake prediction. Proc Natl Acad Sci USA 93: 3748–3755.

Keilis-Borok VI, Knopoff L, Rotwain IM (1980). Burst of aftershocks, long-term precursors of strong earthquakes. Nature 283: 259–263.

Keilis-Borok VI, Kossobokov VG (1990). Premonitory activation of earthquake flow: algorithm M8. Phys Earth Planet Inter 61: 73–83.

Keilis-Borok VI, Primakov I (1997). Earthquake prediction and earthquake preparedness: the possibilities to reduce the damage from earthquakes. In: Fourth Workshop on Non-Linear Dynamics and Earthquake Prediction, 6–24 October 1997, Trieste.

Keilis-Borok VI, Rotwain IM (1990). Diagnosis of time of increased probability of strong earthquakes in different regions of the world: algorithm CN. Phys Earth Planet Inter 61: 57–72.

Kossobokov VG, Romashkova LL, Keilis-Borok VI, Healy JH (1999). Testing earthquake prediction algorithms: statistically significant advance prediction of the largest earthquakes in the Circum-Pacific, 1992–1997. Phys Earth Planet Inter 111: 187–196.

Mirzaei N, Gao M, Chen YT (1999). Delineation of potential seismic sources for seismic zoning of Iran. J Seismol 3: 17–30.

Molchan GM, Dmitrieva OE, Rotwain IM, Dewey J (1990). Statistical analysis of the results of earthquake prediction, based on burst of aftershocks. Phys Earth Planet Inter 61: 128–139.

Nowroozi AA (1976). Seismotectonic provinces of Iran. B Seismol Soc Am 66: 1246–1249.

Nuttli OW (1973). Seismic wave attenuation and magnitude relations for eastern North America. J Geophys Res 78: 876–885.

Panza GF, Peresan A, Magrin A, Vaccari F, Sabadini R, Crippa B, Marotta AM, Splendore R, Barzaghi R, Borghi A et al. (2011). The SISMA prototype system: integrating geophysical modeling and earth observation for time-dependent seismic hazard assessment. Natural Hazards 69: 1179–1198.

Peresan A, Costa G, Panza GF (1999a). Seismotectonic model and CN earthquake prediction in Italy. Pure Appl Geophys 154: 281–306.

Peresan A, Costa G, Panza GF (1999b). A proposal of regionalization for the application of the CN earthquake prediction algorithm to the Italian territory. Ann Geophys 42: 281–306.

Peresan A, Kossobokov V, Panza GF (2012). Operational earthquake forecast/prediction. Rendiconti Lincei 23: 131–138.

Peresan A, Kossobokov V, Romashkova L, Panza GF (2005). Intermediate-term middle-range earthquake predictions in Italy: a review. Earth Sci Rev 69: 97–132.

Peresan A, Rotwain I, Zaliapin I, Panza GF (2002). Stability of intermediate-term earthquake predictions with respect to random errors in magnitude: the case of Central Italy. Phys Earth Planet Inter 130: 117–127.

Peresan A, Zuccolo E, Vaccari F, Gorshkov A, Panza GF (2011). Neo-deterministic seismic hazard and pattern recognition techniques: time-dependent scenarios for North-Eastern Italy. Pure Appl Geophys 168: 583–607.

Rhoades DA, Evison FF (2004). Long-range earthquake forecasting with every earthquake a precursor according to scale. Pure Appl Geophys 161: 47–71.

Rhoades DA, Evison FF (2005). Test of the EEPAS forecasting model on the Japan earthquake catalog. Pure Appl Geophys 162: 1271–1290.

Rotwain IM, Novikova O (1999). Performance of the earthquake prediction algorithm CN in 22 regions of the world. Phys Earth Planet Inter 111: 207–213.

Shebalin PN (1992). Automatic Duplicate Identification in Set of Earthquake Catalogs Merged Together. US Geological Survey Open File Report 92–401 (Appendix II).

Stoecklin J (1968). Structural history and tectonics of Iran: a review. AAPG Bull 52: 1229–1258.

Takin M (1972). Iranian geology and continental drift in the Middle East. Nature 235: 147–150.

Tatar M, Hatzfeld D, Martinod J, Walpersdorf A, Ghafori-Ashtiany M, Chery J (2002). The present-day deformation of the central Zagros (Iran) from GPS measurements. Geophys Res Lett 29: 1927–1930.

Tavakoli B, Ghafori-Ashtiany M (1999). Seismic hazard assessment of Iran. Ann Geophys 42: 1013–1021.

Wells DL, Coppersmith KJ (1994). New empirical relationships among magnitude, rupture length, rupture width, rupture area, and surface displacement. B Seismol Soc Am 84: 974–1002.