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Seismic Gaps and Earthquakes

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Abstract

McCann et al. [1979] published a widely cited "seismic gap" model ascribing earthquake potential categories to 125 zones surrounding the Pacific Rim. *Nishenko* [1991] published an updated and revised version including probability estimates of characteristic earthquakes with specified magnitudes within each zone. These forecasts are now more than twenty and ten years old, respectively, and sufficient data now exist to test them rather conclusively.

For the *McCann et al.* forecast, we count the numbers of qualifying earthquakes in the several categories of zones. We assume a hypothetical probability consistent with the gap model (*e.g.*, red zones have twice the probability of green zones) and test against the null hypothesis that all zones have equal probability. The gap hypothesis can be rejected at a high confidence level. Contrary to the forecast of *McCann et al.*, the data suggest that the real seismic potential is lower in the gaps than in other segments, and plate boundary zones are not made safer by recent earthquakes. For the 1991 *Nishenko* hypothesis, we test the number of filled zones, the likelihood scores of the observed and simulated catalogs, and the likelihood ratio of the gap hypothesis to a Poissonian null hypothesis. For earthquakes equal to or larger than the characteristic magnitude, the

new seismic gap hypothesis failed at the 95% confidence level both the number and ratio tests. If we lower the magnitude threshold by 0.5 for qualifying earthquakes, the new gap hypothesis passes the number test but fails both the likelihood and likelihood ratio tests at the 95% confidence level.

Introduction

The seismic gap hypothesis implies that earthquake hazard is small immediately following a large earthquake and increases with time thereafter on certain fault or plate boundaries [*Sykes and Nishenko*, 1984, p. 5911]. The basic idea behind the gap hypothesis is that stress on a fault will be released by a large earthquake so that one expects no other large earthquake until the stress builds up again. *G. K. Gilbert* [1884] expressed the idea that large earthquakes would deter future ones well before plate tectonic theory was formulated and accepted. *Reid* [1910] suggested that the time of a large earthquake could be predicted approximately from geodetic measurements of coseismic slip during the previous event and the accumulation rate of elastic strain in ensuing years. Thus, the idea of a quasi-periodic occurrence of similar large earthquakes is sometimes referred to as *Reid*'s "elastic rebound" theory. However, elastic rebound and quasi-periodic recurrence are not the same. *Reid*'s 1910 paper discussed a number of basic ideas, including the theory that earthquakes result from elastic strain accumulation, and the speculation that their times might be predictable. In a later paper called "The Elastic Rebound Theory of Earthquakes," *Reid* [1911] omitted the prediction part. We cite this key detail because we challenge the concepts of deterrence and quasi-periodic recurrence, but not the elastic rebound model (that earthquakes result from elastic strain accumulation). The discovery of plate tectonics made the seismic gap theory seem more intuitive, because plate tectonics offered a steady supply of potential displacement and consequent stress. *Scholz* [1990, p. 260] remarked that "A tenet of plate tectonics is that the rates of plate motion must be steady over geologic time periods and must be continuous along plate boundaries. If it is assumed further that a significant portion of this motion must be released seismically, then it follows that segments of plate boundaries that have not ruptured for the longest time are those most likely to rupture in the near future. These places are called seismic gaps."

The seismic gap idea has been applied to long-term forecasting of earthquakes in many regions [*Sykes*, 1971; *Kelleher*, 1972; *Kelleher et al.*, 1973; *McCann et al.*, 1979; *Working Group on California Earthquake Probabilities* (WGCEP), 1988; *Nishenko*, 1991; *Jackson et al.,* 1995; WGCEP, 2002]. Both *McCann et al.* [1979] and *Nishenko* [1989a,b; 1991] gave a long-term earthquake forecast for most of the Pacific Rim. Because *Nishenko* [1991] is almost identical to *Nishenko* [1989a,b] and is more accessible, we mostly use the 1991 reference below. The difference between *McCann et al.* [1979] and *Nishenko* [1991] is that *McCann et al.* specified ranked categories of earthquake potential based on the time since the last large earthquake, while *Nishenko* went further to estimate the probability of a specified characteristic earthquake based both on the elapsed time and estimated mean recurrence time. We will refer to *McCann et al.* [1979] as MNSK [1979].

Because of its wide application and the scientific and social importance of these applications, the seismic gap hypothesis deserves rigorous testing. *Kagan and Jackson* [1991a] tested and rejected the model of MNSK [1979] using ten years of seismic data. They also tested and rejected *Nishenko*'s [1991] new seismic gap hypothesis using five years of data [*Kagan and Jackson*, 1995].

In this paper, we further test the MNSK [1979] and *Nishenko* [1991] hypotheses based on twenty years of data and ten years of data, respectively. We test only whether the predictions of future seismic potential in these papers agree with the subsequent earthquake data; we don't judge the physical reasonableness of the models or possibility of other interpretations of the gap hypothesis, nor do we adjust the models in any way. Our results here are similar to those of our earlier analyses in that the seismic gap models are inconsistent with the earthquake data. However these present results are much more definitive, we have more evidence about which parts of the models lead to their failure, and we can relate earthquake occurrence in the specified zones to the rate of plate tectonic moment accumulation.

The seismic cycle hypothesis is a particular case of the seismic gap hypothesis. The seismic gap or seismic cycle hypothesis has been, and appears still to be, applied to California for predicting seismic hazard (see, for example, WGCEP, 2002). One cannot test the seismic cycle model in a region (e.g., California) because relevant earthquakes occur too infrequently. But the seismic gap hypothesis of *McCann et al.* [1979] and *Nishenko* [1991] can be tested because it is applied to the whole Pacific Rim, thus giving the number of earthquakes which allows statistically rigorous testing. We may assume that if the seismic gap model fails for the circum-Pacific seismic belt, applying this model to smaller regions becomes problematic and needs justification.

Why reexamine previously rejected hypotheses? First, early results based on fewer earthquakes might give misleading results if those quakes were atypical. Now, there can be little doubt that the earthquake record is adequate for testing. Second, many authors missed or ignored the implications of the previous tests, and the gap hypothesis is still frequently accepted with little question. According to the Science Citation Index on May 25, 2003, since 1995 at least 99 published papers referred to “seismic gaps” in the keywords or abstract; 29 of those were published in 2000 or later. Many other papers use the term “seismic cycle” as synonymous with seismic gap. The abstracts reveal that in most of these papers the gap hypothesis was accepted without addressing its conflict with Pacific Rim earthquakes.

In particular, the gap hypothesis in its various modifications is still widely used to assess seismic hazard. *Matthews et al.* [2002, p. 2233] propose "... (1) the probability of immediate rerupture is zero; (2) the hazard rate increases steadily from zero at [time] t=0 to a finite maximum near the mean recurrence time ..." However, in addition to our analysis of seismic gap model performance cited above, *Kagan and Jackson* [1999] investigated all the spatially close pairs of shallow $M \geq 7.5$ earthquakes in the 1976-1998 Harvard CMT catalog and showed that the distribution of inter-earthquake time peaks at the time intervals close to zero. This directly contradicts the statements above and confirms the clustering model of large earthquake occurrence [Kagan and Jackson, 1991b; 1999]. In particular, the commonly echoed statement (1) above is dangerously misleading. Large damaging earthquakes may occur near to and immediately after another. Whether these constitute "rerupture" can be debated, but from a hazard perspective a region does not become safe after a large earthquake.

Our analysis [*Kagan and Jackson*, 1991a] of the first comprehensive gap model [*McCann et al.*, 1979] led to a spirited response [*Nishenko and Sykes*, 1993] and our rebuttal [*Jackson and Kagan*, 1993]. The debate was primarily about how to interpret the MNSK forecast and what criteria to use in selecting test earthquakes. *Nishenko* [1989a,b; 1991] provided a much more specific version of the gap hypothesis which obviated any real debate about earthquake selection criteria. Our later report [*Kagan and Jackson*, 1995] tested and rejected that more explicit hypothesis, and so far there has been no published response by the seismic gap proponents.

MNSK [1979] Pacific forecast

MNSK [1979] summarize six categories of seismic potential for major plate boundaries in and around Pacific regions. These categories range from high to low potential for large earthquakes according to MNSK. They use different colors to denote these six categories: red or category 1 (we will refer to it as 1R in the following paragraphs) denotes the highest seismic potential regions; orange or category 2 (2O in the following paragraphs) denotes the second highest potential regions; green or category 6 (6G) denotes the lowest potential regions; yellow or category 3 (3Y) denotes the regions having an incomplete historic record but a potential for large earthquakes; hatched or category 4 (4H) denotes regions for which plate motion is sub-parallel to the arc; purple or category 5 (5P) denotes the regions which have no historic record of great earthquakes and may not have potential. We numbered the zones using the same numbering scheme as in *Kagan and Jackson* [1991a].

In *Kagan and Jackson* [1991a], we assigned earthquakes to zones by plotting them on the original color map of MNSK. In the present work, we have digitized the MNSK color map and used a computer program to associate earthquakes with zones. We put the digital coordinates of zones on our website: http://moho.ess.ucla.edu/~kagan/mnsk.dat (MNSK [1979] zones) and http://moho.ess.ucla.edu/~kagan/nish.dat (*Nishenko* [1991] zones). The most direct method of testing is to count how many large earthquakes fall into each zone. Here we consider only epicenters and centroids rather than rupture surfaces, because the rupture surfaces are not reported systematically.

In Table 1 we list all shallow earthquakes (depth 70 km or less) with $M_s \geq 7.0$ from the PDE [*Preliminary Determination of Epicenters*, 1999] catalog from June 1, 1978 to December 31, 1998 that fall into the MNSK [1979] zones. In our 1991 paper we assigned fractions of events to different zones if the earthquakes appeared to occur on the boundaries; with our present computer assignment this did not occur. Also our computer program assigned some earthquakes to different zones from assignments in *Kagan and Jackson* [1991a] (those are marked in Table 1). The current designations are not necessarily more accurate, because the MNSK zones are still derived from an analog map, and the zone assignments for earthquakes close to the boundary are always subject to doubt. However, the digitized boundaries have the advantage of reproducibility, and as *Kagan and Jackson* [1991*a*] mention, possible identification errors should average out for a relatively large number of earthquakes.

We also prepared similar tables for two additional sets of earthquakes. The first set is for events with $M_o \geq 7.0$ from the PDE list, where M_o reflects M_s magnitudes from other stations listed in the PDE catalog. In the other set, we use magnitude M_w calculated from the value of scalar seismic moment M_0 reported in the Harvard centroid moment tensor (CMT) catalog [*Dziewonski et al.*, 1999; *Ekström et al.*, 2003]: We used the conversion formula by *Hanks and Kanamori* [1979]

$$M_w = \frac{2}{3}(\log_{10} M_0 - 9.05), \tag{1}$$

where M_0 is measured in Newton meters.

Having compiled tables like Table 1 for all sub-catalogs, we count the number of events occurring in each regional set as well as the number of zones filled by earthquakes. The results are summarized in Table 2. For comparison, we also calculate the average area of zones in each regional set, and the areas are listed in Table 2. Each value in the next-to-last column is the ratio of the number of earthquakes to the total number of zones in the category. Each number in the last column is that fraction of zones in the category filled by earthquakes.

Of the six regional sets, we are most interested in the red, orange and green zones where earthquake potential had been definitely assessed. According to MNSK [1979], the red zones should have the most seismic activity and the green zones should have the least: the probabilities of an earthquake in these zones should be related as

$$P_{red} > P_{orange}, \tag{2a}$$

and

$$P_{orange} > P_{green}. \tag{2b}$$

By contrast, the result summarized in Table 2 shows that the red zones exhibit less seismicity than the other two zone types. For cutoff magnitudes 7.0 or 7.5, the orange and green zones have indistinguishable earthquake potential. We test here for the statistical significance of the disagreement between the observations and the MNSK seismic gap hypothesis according to the formulae (2*a*) and (2*b*).

Number of zones test

We first compare the number of zones filled by earthquakes. For simplicity, we test red versus orange and red versus green, respectively. For comparison, let H_0 be the null hypothesis that zones of all categories have the same probability of having earthquake(s),

$$P_{red} = P_{orange} = P_{green}, \tag{3}$$

and let H_1 be the seismic gap hypothesis in which the probabilities satisfy relation (2). The number of zones filled by earthquakes should obey the binomial distribution. If H_0 is true, the likelihood ratio equals [*Wilks*, 1962, p. 423, exercise 13.5]

$$\lambda = \left(\frac{m}{n}\right)^{m} \left(1-\frac{m}{n}\right)^{n-m} \left(\frac{m_1}{n_1}\right)^{-m_1} \left(1-\frac{m_1}{n_1}\right)^{m_1-n_1} \left(\frac{m_2}{n_2}\right)^{-m_2} \left(1-\frac{m_2}{n_2}\right)^{m_2-n_2}, \tag{4}$$

where n_1 and n_2 are the number of zones of each color, $n = n_1 + n_2$; m_1 and m_2 are the number of zones filled by earthquakes; and $m = m_1 + m_2$. For large *n*, $-2\log\lambda$ follows the Chi-square distribution with one degree of freedom (χ_1^2). Here we use this statistical test to evaluate the seismic gap hypothesis. We would reject the null hypothesis at 95% confidence if the observed λ falls in the lowest 5% of the theoretical distribution.

From data in Table 2*a*, we obtain $\lambda = 0.24$ and $\lambda = 0.53$, respectively, for red to orange zones and red to green zones. Therefore, we cannot reject H_0 since λ is not very small (the corresponding confidence levels are 90.7% and 74.1%, respectively). Similarly, we use the values in Table 2*b* to test whether H_0 is valid for magnitude 7.5. We obtain $\lambda = 0.52$ and $\lambda = 0.38$, respectively, for red to orange zones and red to green zones. The corresponding confidence levels are 74.8% and 83.7%, respectively. Again, as *Kagan and Jackson* [1991*a*] indicated, we cannot reject H_0.

Although the historic record is incomplete in the yellow and purple zones, for completeness we also checked whether the red zones had significantly different earthquake potential from the yellow and purple zones in MNSK. According to MNSK, the yellow zones may have the potential for large earthquakes, and the purple zones may not have the potential for large earthquakes. By Table 2 the red zones actually had lower seismicity than the yellow or purple ones. As in the test above, let H_0 be the hypothesis that zones of all categories have the same earthquake probability,

$$P_{red} = P_{yellow} = P_{purple} . \tag{5}$$

The hypothesis (5) could not be rejected with 95% confidence.

Failure to reject the null hypothesis does not by itself mean that we can reject the seismic gap hypothesis. To test the seismic gap hypothesis, let us assume that

$$P_{orange} = P_{green} = 0.48 , \tag{6a}$$

and

$$P_{red} = 1.5 P_{orange} , \tag{6b}$$

or

$$P_{red} = 2.0 P_{green} , \tag{6c}$$

where P_{orange}, P_{green} and P_{red} are the respective probabilities that in 20 years the orange, green and red zones would experience an $M \geq 7.0$ earthquake. The value 0.48 in (6*a*) comes from Table 2 in which the fraction of orange and green zones filled by earthquakes is about 0.48. Table 2 shows that the numbers of red zones filled by earthquakes are 4 or 5 according to different catalogs. Now we calculate under H_1 the probability that 5 or fewer of the 17 red zones would be filled by $M \geq 7.0$ earthquakes:

$$P(m \leq 5) = \sum_{i=0}^{5} \binom{n}{i} (P_{red})^i (1 - P_{red})^{n-i} , \tag{7}$$

where n = 17 is the number of red zones. For case (6*b*) we calculate that such probability is 3.2×10^{-4}, and for case (6*c*) the probability is 8.6×10^{-14}. Similarly, the probabilities that 4 or fewer of the 17 red zones would be filled by $M \geq 7.0$ earthquakes are 3.7×10^{-4} for (6*b*) and 8.7×10^{-14} for (6*c*), respectively. These small probabilities mean that the gap hypothesis as given by (6) should be rejected with high confidence. The results of the tests are similar to *Kagan and Jackson* [1991a], except that now we can confidently reject the gap hypothesis by test (7).

Nishenko and Sykes [1993] suggest that MNSK predictions are for $M \geq 7.5$ earthquakes. Let us assume that $P_{orange} = P_{green} = 0.25$ for $M \geq 7.5$. We calculate under H_1 that 2 or fewer of the 17 red zones would be filled by $M \geq 7.5$ earthquakes with a probability of 0.020 for case (6*b*) and 0.001 for case (6*c*). These small probabilities also indicate that the gap hypothesis should be rejected for large earthquakes ($M \geq 7.5$).

In summary, the record of which zones have been ruptured by earthquakes is consistent with the proposition that all zones have the same rupture probability. Assuming equality always led to a result that can be explained by random variations within the usual 95% confidence limits. On the other hand, the assumption that identified gaps have a probability twice that for previously filled zones does not match the data. Both of these statements hold whether the threshold for rupture is taken as magnitude 7.0 or 7.5.

Number of earthquakes test

Besides comparing the number of filled zones, we may also compare the numbers of quakes in different zones. The difference is that above we counted only the first event in any zone (because it filled the zone), and here we count all quakes. The data in Table 2 suggest that green zones are actually more active than red. To examine that idea, we test H_{-1}, the antithesis of the gap model, against the null hypothesis. For both hypotheses we assume that the number of earthquakes in different zones obeys the Poisson distribution, and ask whether the rates are higher in the red zones than in the others. The null hypothesis assumes the rates are equal. If H_0 is true, the likelihood ratio equals [*Wilks*, 1962, p. 424, exercise 13.10]

$$\lambda = \left(\frac{m}{n}\right)^{m} \left(\frac{m_1}{n_1}\right)^{-m_1} \left(\frac{m_2}{n_2}\right)^{-m_2}, \tag{8}$$

where n has the same meaning as in (4), and m is the number of earthquakes. The quantity $-2\log\lambda$ is also distributed for large n according to the χ_1^2. Using the values in Table 2, for $M \geq 7.0$ we obtain $\lambda = 0.016$ and $\lambda = 0.017$ for red to orange and red to green, respectively. Both values are so small that we can reject the null hypothesis ($P_{red} = P_{orange} = P_{green}$) at a confidence level of 99.6% in favor of H_{-1}. That is, for $M \geq 7.0$ the data imply that for earthquakes numbers

$$P_{red} < P_{orange}, \tag{9a}$$

and

$$P_{red} < P_{green} . \qquad (9b)$$

This new result is much stronger than that obtained in *Kagan and Jackson* [1991a] (92.5% and 92%, respectively).

The same procedure is applied for $M \geq 7.5$. In this case, the likelihood ratios are λ = 0.41 and λ = 0.17 for red to orange and red to green, respectively. For λ = 0.17, we can reject the null hypothesis at the confidence level of 94.0%; for λ = 0.41, the corresponding confidence level is 82.1%. Thus, using the $M \geq 7.5$ earthquake numbers, we cannot reject the null hypothesis that the red and orange zones have the same potential.

Using the values in Table 2, we also tested red zones vs. yellow and purple (hypothesis equivalent to equation (5)). For magnitudes 7.0 and 7.5, we cannot reject with 95% confidence the null hypothesis that the red zones have the same average earthquake rate as the yellow and purple zones.

To summarize our tests of the MNSK model, we consider magnitude thresholds of 7.0 and 7.5, and we count either ruptured zones or the total number of earthquakes in them. We consider the most relevant zone categories (colors) in pairs. Regardless of which choice we make for threshold or counting method, the various colors of zones have statistically indistinguishable earthquake potential, with one exception. That exception is that the red zones show a significantly lower earthquake rate than the green or orange ones for $M \geq 7.0$.

Nishenko's circum-Pacific earthquake forecast

As in *Kagan and Jackson*'s [1995] paper, we use the digitized circum-Pacific color map to define zones, and we use conditional probabilities as specified in *Nishenko*'s Appendix table

[*Nishenko*, 1991, pp. 249-251]. We exclude from consideration any zone for which there is no probability value defined. In all cases, when two values of magnitude or probability are specified, for consistency we take the smaller characteristic magnitude value and averaged the two probabilities. We interpreted the probability value of “less than 1%” as 0.5%. We made the same adjustments to *Nishenko*'s [1991] map and table as in *Kagan and Jackson* [1995]. The adjusted zones, their characteristic magnitudes, and probabilities are listed in Table 3. We assume that the probabilities are for the occurrence of at least one qualifying earthquake in a given zone. At the end of the table, probabilities have been summed and this sum interpreted as the number of expected earthquakes. Thus, we count only the first qualifying event in each zone. The success or failure of a hypothesis is based on the earthquake “record,” which can be represented by an ordered list of 98 binary values: 1 for each filled zone, 0 for all others.

Poisson Null Hypothesis

We compare the new seismic gap hypothesis, as described by *Nishenko* [1991], with the Poisson null hypothesis. If we consider the null hypothesis to be that earthquakes result from a Poisson process with a rate of r in any zone, the probability that at least one qualifying earthquake would randomly occur is

$$p_0 = 1 - \exp(-rt)\,. \tag{10}$$

The r-values are calculated from past seismicity and the method is described in detail by *Kagan and Jackson* [1994]. To estimate r-values we use a smoothed version of the global seismicity represented by the CMT catalog from 1977 through 1988. We do not attempt to update r-values with earthquakes since 1988 so that both the gap and null hypotheses rely on pre-1989 data only.

Table 3 gives zone probabilities for the null hypothesis appropriate for comparison with *Nishenko*'s characteristic earthquake probabilities. The null probabilities are labeled “P Pr.”. Tables 4*a* and *4b* list the earthquakes with magnitude greater than or equal to the characteristic magnitude M_c and M_c -0.5 in the CMT and PDE catalogs. Five earthquakes in the PDE and CMT catalogs, respectively, qualify as zone fillers for the characteristic magnitude M_c. If we use M_c -0.5 as a magnitude threshold, eight additional earthquakes in the PDE catalog and seven additional in the CMT qualify as zone fillers.

Statistical Testing of Forecasts

We employ three kinds of statistical tests to evaluate the new seismic gap hypothesis and Poisson null hypothesis. In each case we define a statistic (a measurable feature of the earthquake catalog), simulate 10^5 synthetic records for each of the two hypotheses, compute the defined statistic for both the observed and simulated earthquake records, and compare the observed statistic with the simulated values. If the observed statistic falls safely within the range of simulated values, we judge that the observed catalog “looks like” those that satisfy the hypothesis by construction. Otherwise we reject the hypothesis as an explanation for the observed record. To simulate earthquake records consistent with a given hypothesis, we generate a suite of random numbers between 0 and 1. Then we compare those numbers with the probability for the appropriate hypothesis. If the random number is less than the probability, we consider the zone filled. Otherwise, we assume there is no earthquake in the zone.

- (*i*) The “*N* test,” based on the total number of zones filled by earthquakes. We generate 1×10^5 simulated records and counted *N*, the number of filled zones for each. Figure 1 shows the cumulative distribution of simulated *N* values for both the new seismic gap hypothesis and the null hypothesis. These curves are cumulative sample distributions, with the number of simulations having *N* or fewer filled zones plotted as the height of the horizontal line segment to the right of a hypothetical vertical line through *N*. The actual values of *N* observed in CMT and PDE catalogs are also shown as vertical lines in Figure 1. Here we use a two-tailed test at the 95% confidence level, rejecting a hypothesis if the observed number of filled zones is either too small or too large compared to the predicted value. Thus, we reject a hypothesis if fewer than 2.5% or more than 97.5% of the simulations has *N* less than or equal to the observed value. We calculate the probabilities of random score less than catalog score, and list them in Table 5. Given the *N* test results in Table 5, we reject the new seismic gap hypothesis at the 95% confidence level for the characteristic magnitudes. The null hypothesis passes the *N* test.

Compared to the actual number of events, the new gap hypothesis over-predicted the earthquake numbers. We plot the concentration diagrams of the predicted and actual number of events in Figure 2: for each model, we sorted the zones in descending order by predicted probabilities per area. Then we plotted the cumulative probabilities and the cumulative earthquake count in the sorted zones. The left panel is for the *Nishenko* [1991] hypothesis, and the right for the Poisson null hypothesis. The smooth curves in Figure 2 demonstrate the relation between the fraction of total area and fraction of theoretical earthquake probability. The step curves show how the fractions of total area and total earthquakes relate. As shown in Figure 2, the *Nishenko* model predicted more than 17.5 events, and the Poisson null model predicted only 3.3 earthquakes. Since the observed number of events in both the PDE and the CMT catalogs is 5, the *Nishenko* model fails but the Poisson null hypothesis passes the *N* test.

- (*ii*) The “*L* test,” based on the logarithm of the likelihood of a particular set of zones being filled. The score for this test is [*Martin*, 1971, p. 76]

$$\begin{aligned} L &= \sum_{i=1}^{n} c_i \log(p_i) + \sum_{i=1}^{n} (1-c_i)\log(1-p_i) \\ &= \sum_{i=1}^{n} \log(1-p_i) + \sum_{i=1}^{n} c_i \left[\log\left(\frac{p_i}{1-p_i} \right) \right], \end{aligned} \tag{11}$$

where L is the log of the joint probability of the particular outcome, n is the total number of zones, p_i is the probability forecasted by the new gap or the Poisson model for the ith zone, and c_i is equal to 1 if the ith zone is filled by a qualifying earthquake in the catalog, and 0 otherwise. The sums are over all zones. We use this procedure as a one-tailed test at the 95% confidence level, rejecting the lower 5%, so that we do not reject exceptionally high scores that would occur if only the highest probability zones are filled. Note that if the zone probabilities are less than 0.5 (true here for both hypotheses), the largest possible likelihood occurs if there are no zones filled. Thus the *L* test should not be used without applying the *N* test as well [*Kagan and Jackson*, 1995]. Figures 3*a* and 3*b* show the results of the *L* test for the new seismic gap hypothesis and the Poisson null hypothesis, respectively. These results are in the form of a cumulative count versus log likelihood using the characteristic magnitude threshold. The vertical lines show the corresponding log likelihood value for the records derived from the CMT and PDE catalogs. From Figure 3 and Table 5, we see that the new seismic gap and the null hypotheses both passed the *L* test for characteristic magnitude.

- (*iii*) The “*R* test,” based on a likelihood ratio test against a reasonable null hypothesis. The test score is given by [*Martin*, 1971, pp. 120-147]

$$R_1 = L_{11} - L_{21} = \sum_{i=1}^{n} \log\left(\frac{1-p_{1i}}{1-p_{2i}}\right) + \sum_{i=1}^{n} c_{1i} \log\left(\frac{p_{1i}(1-p_{2i})}{p_{2i}(1-p_{1i})}\right) \ , \tag{12a}$$

and

$$R_2 = L_{12} - L_{22} = \sum_{i=1}^{n} \log\left(\frac{1-p_{1i}}{1-p_{2i}}\right) + \sum_{i=1}^{n} c_{2i} \log\left(\frac{p_{1i}(1-p_{2i})}{p_{2i}(1-p_{1i})}\right), \tag{12b}$$

where p_i, n, c_i and L have the same meanings as in equation (11). We proceed as follows. First we generate 10^5 synthetic records consistent with the new seismic gap hypothesis, score each one using both the gap probabilities (to obtain L_{11}) and the null probabilities (to obtain L_{21}), take their difference, and sort them from smallest to largest to get a cumulative distribution of R_1 values corresponding to the gap hypothesis. Then we do the same for the synthetic records generated using the null hypothesis. We then choose a critical value of R, such that we reject the null hypothesis in favor of the gap hypothesis if the R score for the observed record is greater than the critical value. The effectiveness of the test is measured by two probabilities: that of falsely rejecting the null hypothesis if it were true, and that of falsely rejecting the gap hypothesis if it were true. The probability can be estimated by the fraction of synthetic null records whose score is less than the critical value. It implies that we use this procedure as a one-tailed test at the 95% confidence level, rejecting the lower 5% so that we do not reject a model if the model is too good. Standard procedure is to choose a critical value that balances these two error probabilities, estimate the score for the observed data, and then accept the null or the test hypothesis depending on whether its score is less or greater than the critical value. Figure 4 shows the result of the R test for characteristic magnitudes. In this case a very powerful test is possible if the critical value is chosen as the R score for the PDE or the CMT catalogs. From Figure 4, we see that the PDE scored R is -16, and the CMT scored -11. For the PDE catalog, about 20% of the synthetic null records scored more than -

16, and nearly no synthetic gap records scored less than -16. Thus, for the PDE catalog, the probability of falsely rejecting the null hypothesis is about 80%, but the probability of falsely rejecting the gap hypothesis is less than 1%. Thus at the 95% confidence level the null hypothesis should not be rejected, but the gap hypothesis should. For the CMT catalog the probability of falsely rejecting the null hypothesis is about 97.5% (only about 2.5% synthetic scores exceed the CMT scored R value), but the probability of falsely rejecting the gap hypothesis is less than 1%. Therefore, we should reject the gap hypothesis, but not the null hypothesis at the 95% confidence level.

To find why the R score for CMT catalog is greater than about 97% of the null hypothesis catalogs, we checked the five earthquakes falling into the zones. We find that three earthquakes fall into the relatively high probability zones: No.1, 8 and 11 in Table 4*a*. The average probability of all zones is 0.034, but the average of the five filled zones is 0.045. Therefore, the null hypothesis shows too good a forecast for the CMT catalog.

Note that the probabilities associated with a hypothesis are used in two ways: in generating synthetic records consistent with the hypothesis and scoring hypotheses to test their consistency. The test can be applied to any record, including that for the observed data and records generated using another hypothesis.

The nature of the L and R tests can be illustrated using a "cross likelihood plot," as shown in Figure 5. For each record, the likelihood score L_1 is calculated using the gap probabilities, L_2 is calculated using the null-hypothesis probabilities, and the two are plotted on a graph. Two large crosses in Figure 5 show the scores for records corresponding to the PDE and CMT catalogs. Small dots show the scores for synthetic records generated using the gap probabilities, and small crosses of "plusses" show the scores for synthetic null-hypothesis records. The diagonal lines show the locus of points corresponding to the PDE scored and the CMT scored *R*-values. Again, the figure shows that for the PDE catalog, the probability of falsely rejecting the null hypothesis is large, but the probability of falsely rejecting the gap hypothesis is very tiny.

Alternate Magnitude Threshold

The characteristic earthquake magnitude is uncertain because it is estimated from measurements. Therefore, we decided to try another magnitude threshold, M_c - 0.5, to test the new seismic gap and the Poisson null hypotheses. We also employ the *N*, *L* and *R* tests. The test results, listed in Table 5, show that both the new seismic gap hypothesis and the Poisson null hypothesis passed the *N* test. For the *L* test, however, both hypotheses failed. For the *R* test, the gap hypothesis again failed both the PDE and CMT catalogs, but the null hypothesis passed.

Discussion

MNSK [1979] pointed out that the forecasts were made subject to several assumptions and limitations. However, many of these assumptions and limitations are ambiguous, so it is very difficult for others to distinguish which earthquake qualifies for the forecast and which does not. In such a case, we cannot test very strictly. Fortunately, MNSK [1979] clearly stated that their forecast applied to shallow earthquakes of magnitude 7 or greater. And they provided the relative potential of red, orange and green zones. On the one hand, we can test MNSK [1979] by counting the number of real earthquakes in each type of zone, and on the other hand, we can assume a potential ratio and test quantitatively.

However, some other problems exist. Because we did not count the earthquakes of magnitude even a little less than 7 and those of epicenter even a few kilometers out of the zones, the inaccuracy of earthquake location and magnitude may bring out some errors. To decrease such errors, we used not only the PDE but also the CMT catalog. Nevertheless, both catalogs show the same potential trend: the red zones have lower potential than the orange and green zones, and the orange and green zones have almost the same potentials. Moreover, if we also consider the area of each zone type, it is more obvious that the potential of red zones is lower than those in orange and green zones. We also test the gap hypothesis using a cutoff magnitude of 7.5 since *Nishenko and Sykes* [1993] stated that the forecast is for magnitude 7.5 or greater. For this hypothesis, the results are almost the same as with magnitude 7 so the alternate magnitude cannot save the seismic gap hypothesis either.

Comparing the results in the "ten years after paper" [*Kagan and Jackson*, 1991a] with those here, we find great similarity. We rejected the gap hypothesis in that earlier paper, and reject it again now using more (20 years) data.

Because *Nishenko* [1991] quantitatively described the seismic hazards of large and great characteristic earthquakes along segments of the circum-Pacific seismic zone, we can test his forecast more rigorously. We also used both the PDE and CMT catalogs to reduce errors in earthquake location and magnitude. In the statistical tests, we adopted a two-tailed rule for the N test, which means that we reject a model when it predicts too many or too few events. However, we adopted a one-tailed rule for the L and R tests because we reject only those models significantly inconsistent with the observations. We do not reject a model if it is too consistent with observations. For characteristic magnitude, both the L and R tests indicate that the new gap hypothesis should be rejected. For comparison, we also tested the Poisson null hypothesis. Contrary to the new gap hypothesis, the Poisson null hypothesis passed most tests. For the magnitude threshold M_c-0.5, both the *L* and *R* tests show that the new gap hypothesis should be rejected. The Poisson null hypothesis failed the *L* tests only.

There is almost no change in testing results between this paper and those in the paper “five years after” [*Kagan and Jackson*, 1995]. Both rejected the new seismic gap hypothesis for forecasting too many earthquakes. However, there is some change in the seismicity of large earthquakes that fall into the zones. Figure 2 shows the numbers of large earthquakes in catalogs and the numbers forecasted by the new seismic gap hypothesis and the Poisson null hypothesis. Obviously, the new gap hypothesis forecast far more earthquakes than occurred, and our simulations show that the discrepancy cannot be explained reasonably by random variations. The Poisson null hypothesis forecast slightly too few earthquakes, but our simulations show that this difference is consistent with random fluctuations.

Why do the seismic gap models not match the data? The gap models are based on an assumption that most slip on a plate boundary segment occurs in earthquakes of a characteristic size. However, the magnitude distributions for earthquakes in the several kinds of zones described in *McCann et al.* [1979] had the same shape as the distribution of all earthquakes in the Harvard catalog [*Kagan*, 2002]. In this paper *Kagan* analyzes earthquake size distributions in various groups of the MNSK and *Nishenko* [1991] zones, and shows that they can be approximated by the tapered Gutenberg-Richter relation having the same values for its basic parameters. This fact suggests that the characteristic earthquake hypothesis is not valid, or that the characteristic earthquake sizes and consequent recurrence times were severely underestimated in *Nishenko* [1991]. In addition, the uncertain amount of aseismic slip makes estimating recurrence time difficult. Non-uniform strain accumulation due to the influence of remote earthquakes (elastic or viscoelastic) may also affect estimates of earthquake recurrence time. Moreover, frequent small earthquakes also release strain energy, which again makes it difficult to estimate the recurrence time of a fault segment. Since an important factor in the gap hypothesis is such estimation, errors or difficulties in it can incapacitate the gap hypothesis. By comparison with the time-dependent seismic gap hypothesis, the null hypothesis assumes a Poisson distribution of earthquake recurrence times.

We used the Poisson model to forecast long-term earthquake potential in western Pacific [*Jackson and Kagan*, 1999; *Kagan and Jackson*, 2000] and in China [*Rong and Jackson*, 2002] by smoothing past seismicity. We tested these forecasts against earthquakes which occurred after the forecasts have been issued. In both of these cases we find that earthquakes are quite compatible with the smoothed seismicity model.

Although the Poisson model outperforms the seismic gap hypothesis, its validity should not be taken as proven. In addition to our results showing that earthquake clustering explains circum-Pacific seismicity better than the Poisson or a quasi-periodic (seismic gap or seismic cycle) hypothesis, there are many other indications of clustering in strong earthquake occurrence [*Kagan and Jackson*, 1991b; 1999]. Our recent papers [*Jackson and Kagan*, 1999; *Kagan and Jackson*, 2000] incorporate short-term clustering (foreshock-mainshock-aftershock sequences) to estimate earthquake potential in western Pacific regions. However, it seems likely that a longer-term clustering is also present; it should be included in methods of forecasting earthquakes.

As another possibility we introduce models that account for tectonic motion in evaluating earthquake potential *[Bird et al.*, 2000; *Kagan*, 2002]. These models may perform better for long-term forecasts than those based on extrapolating recent seismicity by smoothing earthquake distribution [*Jackson and Kagan*, 1999; *Kagan and Jackson*, 2000].

Conclusions

We statistically test the forecasts of circum-Pacific seismicity issued more than 20 years ago by MNSK [1979] and more than 10 years ago by *Nishenko* [1991]. On the basis of these tests, we draw the following conclusions:

1. The gap hypothesis did not forecast large earthquakes well.

2. The hypothesis that the red gaps of MNSK [1979] are significantly more prone to strong earthquakes than the green and orange zones can be rejected with high confidence. On the contrary, the red zones were less often filled and had lower earthquake rates than the orange and green zones.

3. The new seismic gap hypothesis [*Nishenko*, 1991] forecast far more earthquakes than occurred. For the characteristic magnitude, the new gap hypothesis failed both number and likelihood ratio tests. For the magnitude of M_c-0.5, it failed both the likelihood and likelihood ratio tests.

4. The Poisson null hypothesis passed most of the tests and outperformed the new gap hypothesis.

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Figure captions

Figure 1. Illustration of the *N* test for the new seismic gap and null hypotheses, using the characteristic magnitude as a threshold. The vertical lines show the actual values of *N* observed in CMT and PDE catalogs (note that both catalogs have 5 qualifying events). The step curves are cumulative sample distributions (see text for a more detailed explanation). The new seismic gap hypothesis fails, but the null hypothesis passes, at the 95% confidence level.

Figure 2. Concentration plot of observed (the step curve) and forecast earthquake rates (the smoothed curves) for Jan. 1990 to Dec. 1999. (Left) *Nishenko* [1991] hypothesis. The solid curve shows cumulative number of events forecasted by the *Nishenko* [1991] model. The dashed and the dotted curves illustrate the cumulative number of earthquakes in PDE and CMT catalogs, respectively. The *Nishenko* model over-predicted events by more than two third. (Right) Poisson Null hypothesis. The solid curve shows cumulative number of events forecasted by the Poisson Null model. It illustrates that the predicted rate is well concentrated and agrees well with locations of earthquakes occurring after the forecast.

Figure 3. Illustration of the *L* test, using the characteristic magnitude as a threshold. The likelihood scores for the PDE and CMT catalogs are different as different zones are filled under the two catalogs. (*a*) *L* test for the new seismic gap hypothesis. (*b*) *L* test for the Poisson null hypothesis. Both the new seismic gap and the Poisson null hypotheses pass the test.

Figure 4. Illustration of the *R* test for the new seismic gap and null hypotheses, using the characteristic magnitude as a threshold. The seismic gap hypothesis fails for both the PDE and the CMT catalogs. The null hypothesis passes for both catalogs.

Figure 5. Cross-likelihood test for the new seismic gap and null hypotheses, using the characteristic magnitude as a threshold. Small dots show the scores for synthetic records generated using the gap probabilities, and small crosses of "plusses" show the scores for synthetic null-hypothesis records. The diagonal line shows the locus of points corresponding to the critical values for the PDE and the CMT catalogs. The probability of falsely rejecting the null hypothesis is large (>80% for the PDE catalog, and >97% for the CMT catalog), and the probability of falsely rejecting the gap hypothesis is less than 1% for both catalogs.

Figure 1

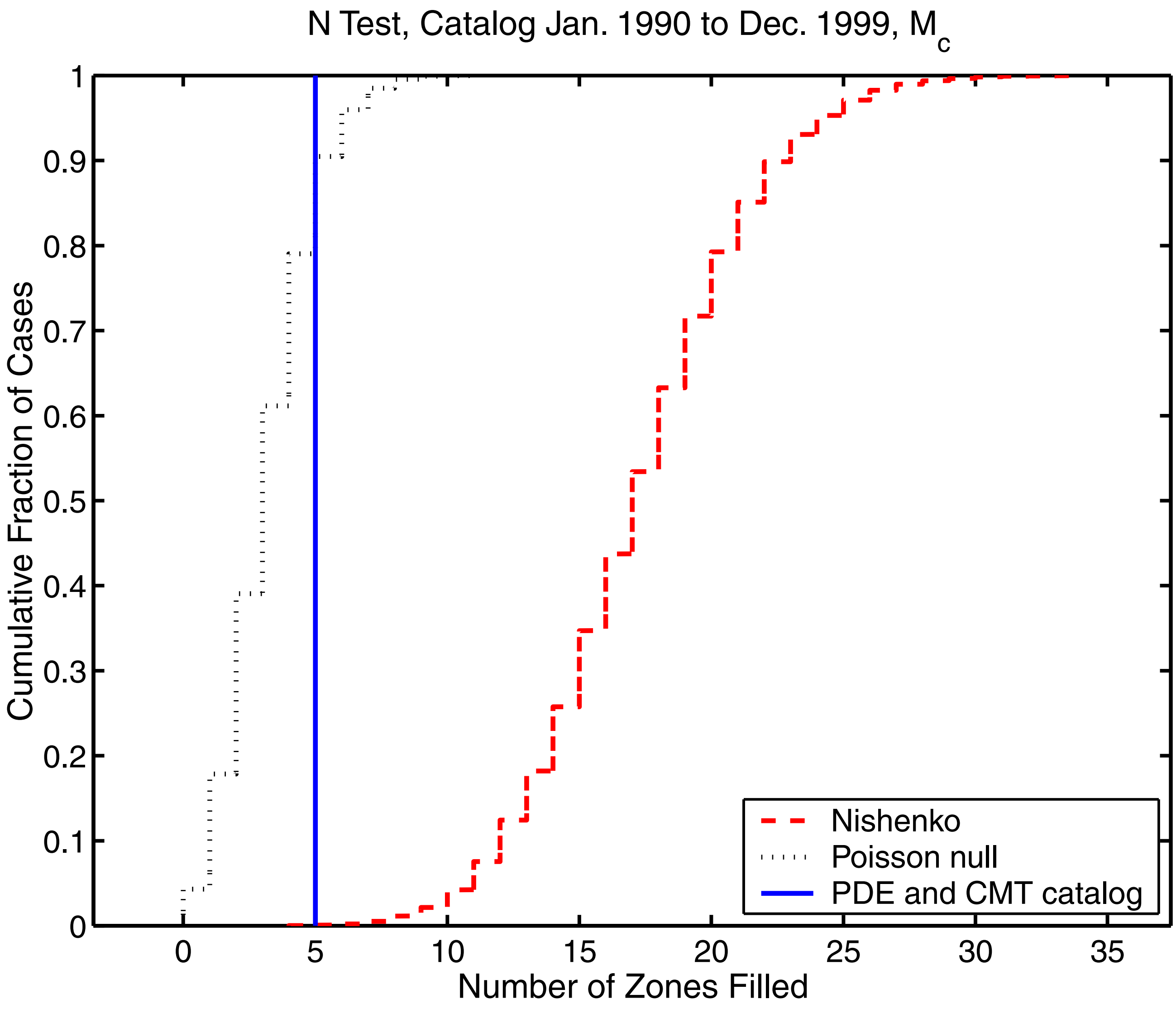
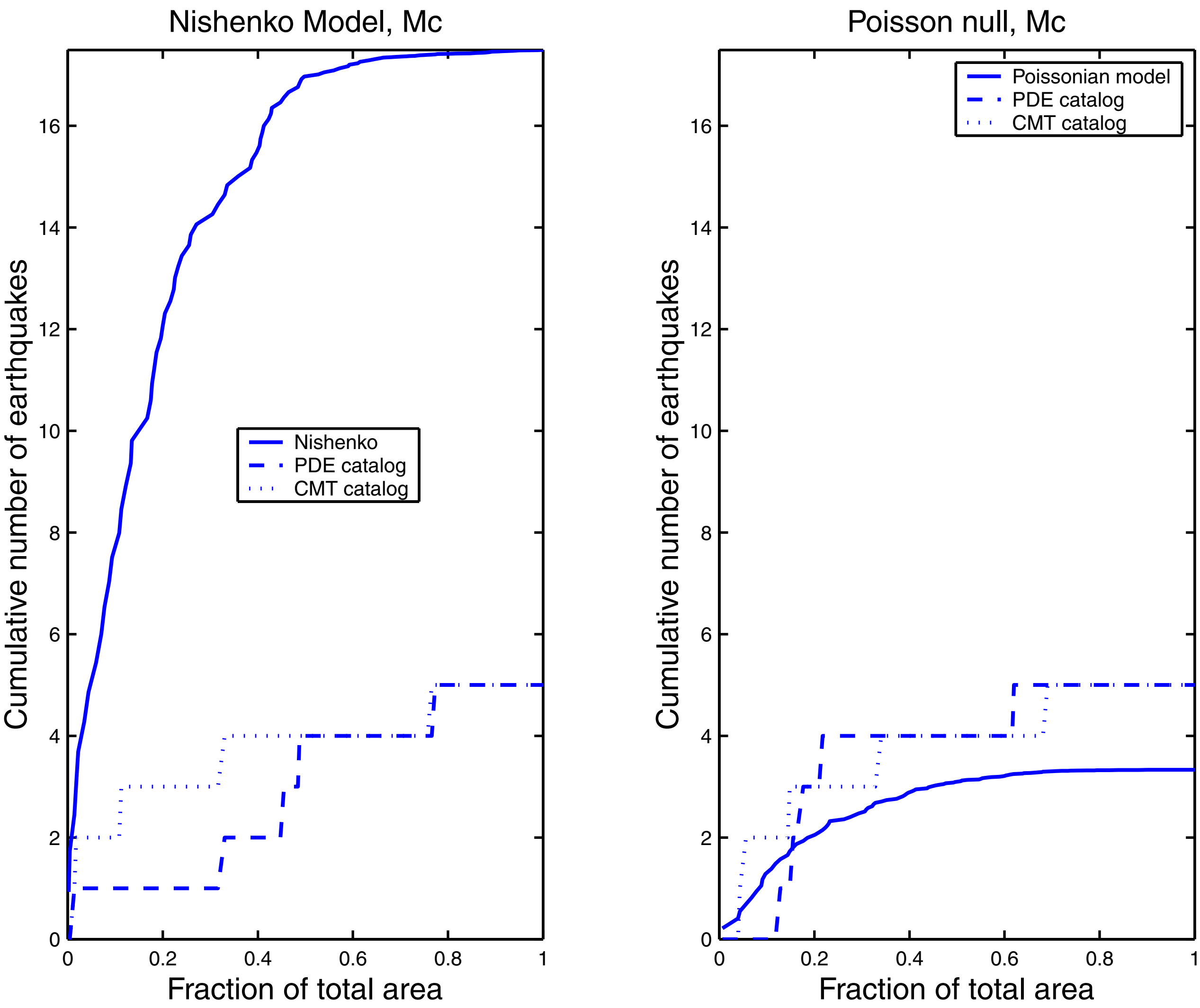

N Test, Catalog Jan. 1990 to Dec. 1999, M_c
Cumulative Fraction of Cases
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
Number of Zones Filled
0
5
10
15
20
25
30
35
Nishenko
Poisson null
PDE and CMT catalog

Figure 2.



Nishenko Model, Mc
Poisson null, Mc
Cumulative number of earthquakes
Fraction of total area
Nishenko
PDE catalog
CMT catalog
Poissonian model
PDE catalog
CMT catalog
0
2
4
6
8
10
12
14
16
0
0.2
0.4
0.6
0.8
1

Figure 3a.

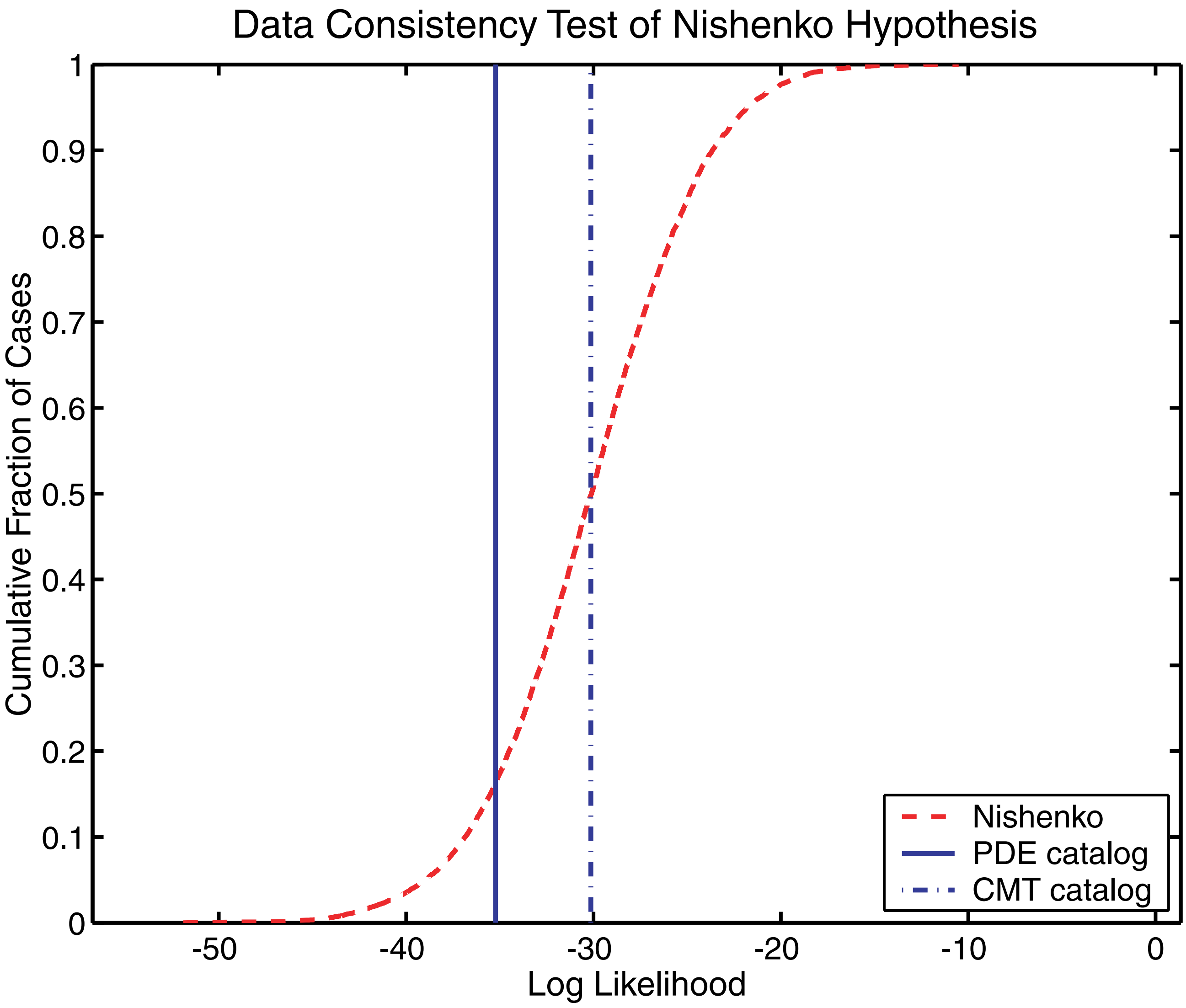

Data Consistency Test of Nishenko Hypothesis
Cumulative Fraction of Cases
Log Likelihood
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
-50
-40
-30
-20
-10
0
Nishenko
PDE catalog
CMT catalog

Figure 3b

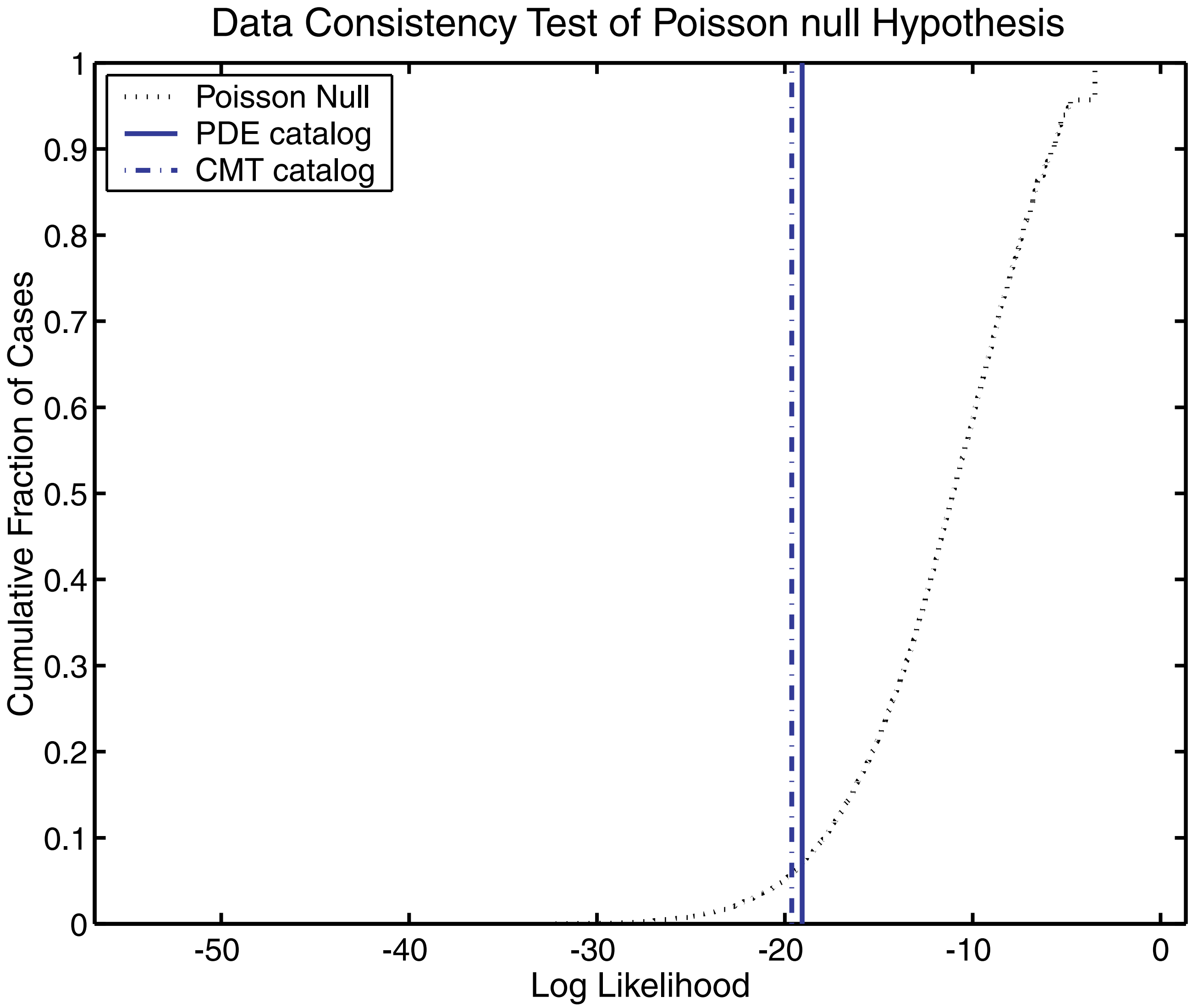
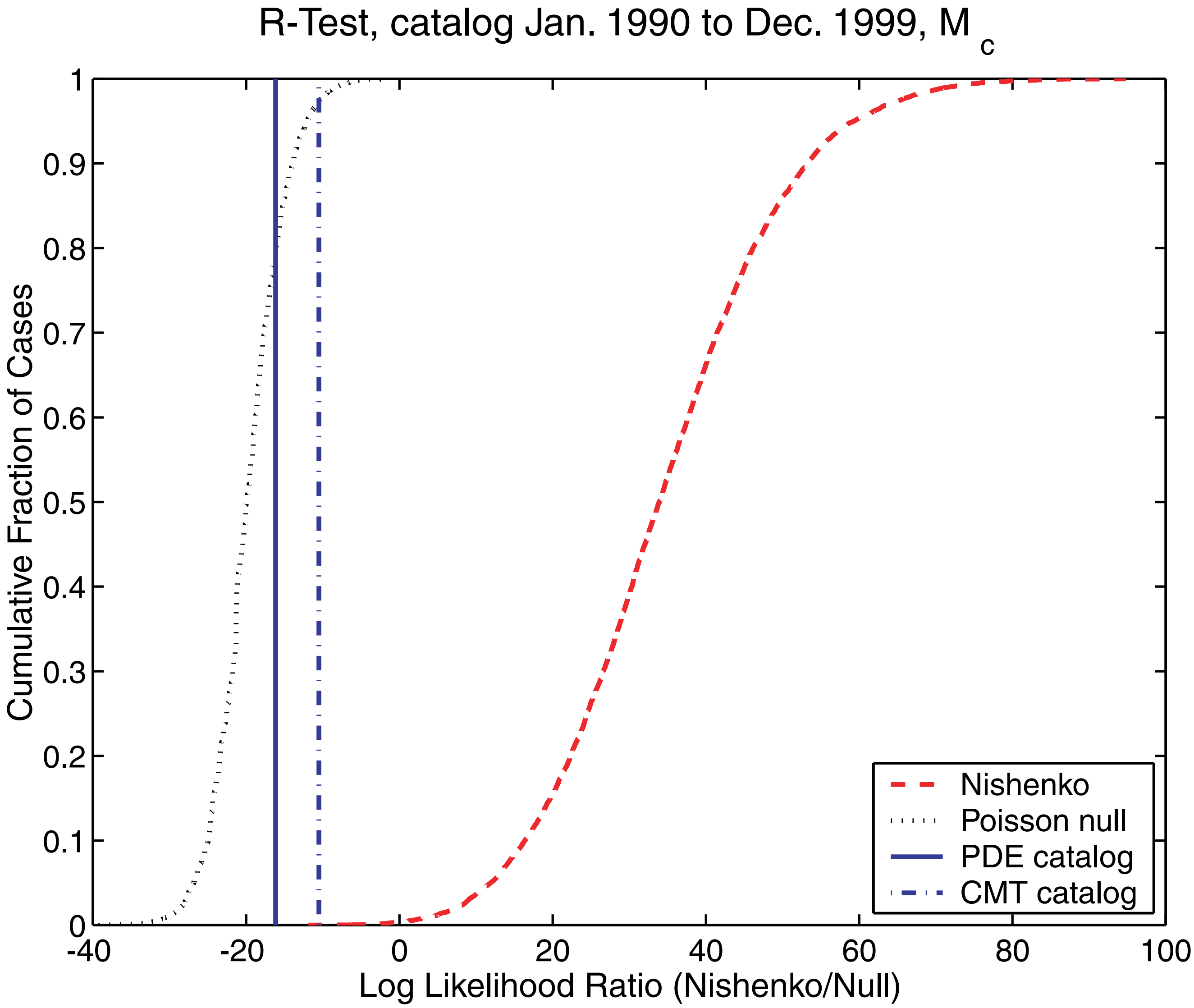

Data Consistency Test of Poisson null Hypothesis
Poisson Null
PDE catalog
CMT catalog
Cumulative Fraction of Cases
Log Likelihood
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
-50
-40
-30
-20
-10
0

Figure 4.



R-Test, catalog Jan. 1990 to Dec. 1999, M c
Cumulative Fraction of Cases
Log Likelihood Ratio (Nishenko/Null)
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
-40
-20
0
20
40
60
80
100
Nishenko
Poisson null
PDE catalog
CMT catalog

Figure 5.

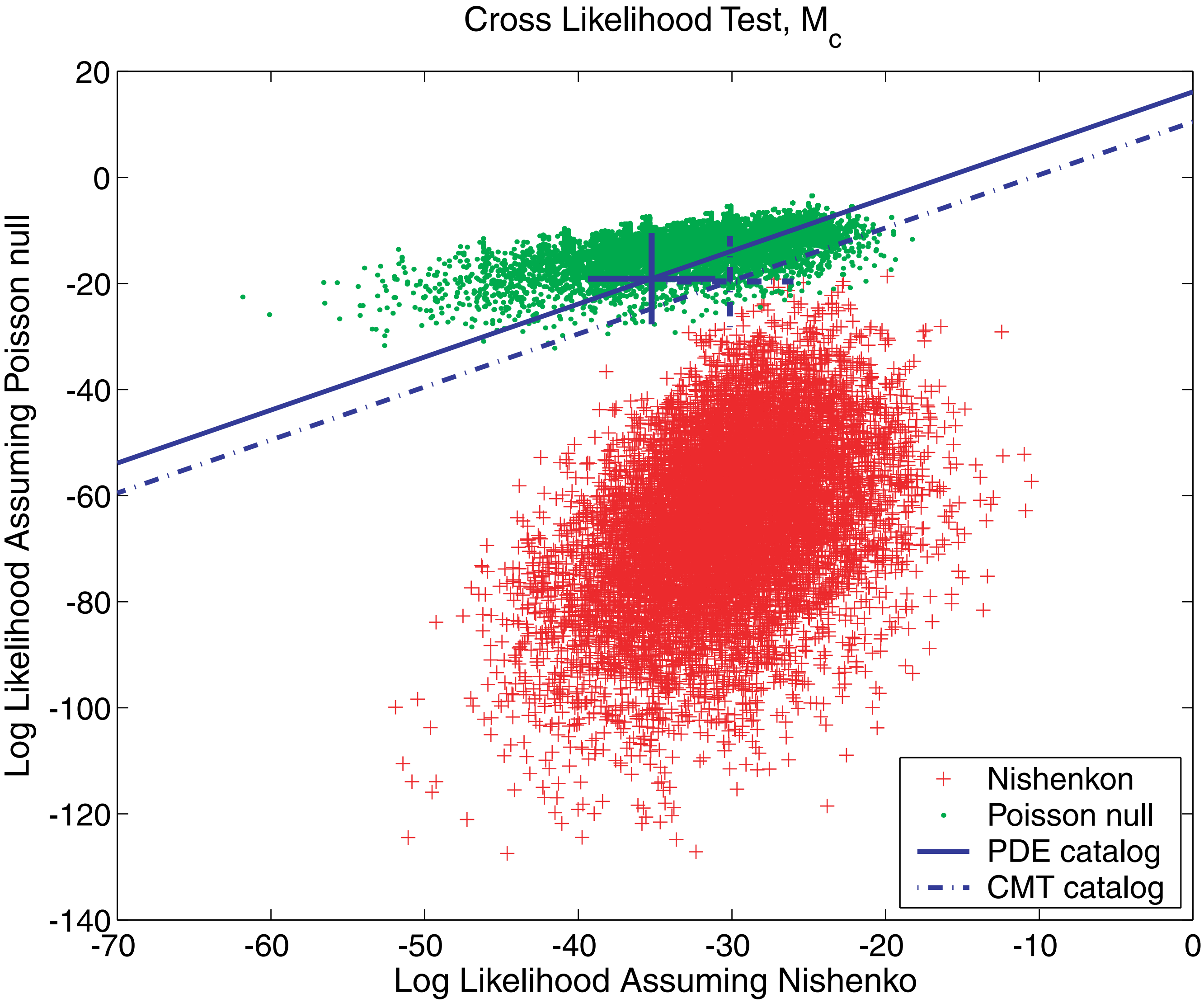

Cross Likelihood Test, M_c
Log Likelihood Assuming Poisson null
Log Likelihood Assuming Nishenko
20
0
-20
-40
-60
-80
-100
-120
-140
-70
-60
-50
-40
-30
-20
-10
0
Nishenkon
Poisson null
PDE catalog
CMT catalog

Table1. PDE list of earthquakes with M_s≥7.0 in Circum-Pacific region and their attribution to MNSK zones.

Earth-quakes	Time			Coordinates		Depth (km)	M_S	MNSK Zone	Notes
	Year	Month	Day	Longitude	Latitude				
*1	1978	6	12	142.028E	38.190N	44	7.7	21O	-
2	1978	6	17	172.264W	17.098S	33	7.0	19Y	
3	1978	7	23	121.512E	22.282N	17	7.4	25O	
*4	1978	8	23	85.222W	10.204N	56	7.0	9G	-
5	1978	11	5	162.136E	11.132S	33	7.1	31G	
*6	1978	11	29	96.591W	16.010N	18	7.7	12G	-
7	1978	12	23	122.075E	23.247N	33	7.0	11R	
*8	1979	2	28	141.593W	60.642N	15	7.1	5Y	-
*9	1979	3	14	101.276W	17.813N	49	7.6	16O	13G
10	1979	8	26	122.096E	19.066N	15	7.1	9P	
11	1979	10	23	161.284E	10.615S	22	7.1	31G	
*12	1979	12	12	79.358W	1.598N	24	7.7	7G	7G/5O
13	1980	2	23	146.753E	43.530N	44	7.0	19G	
14	1980	7	8	166.381E	12.410S	33	7.5	32G	
15	1980	7	17	165.916E	12.525S	33	7.9	32G	
16	1980	10	25	169.853E	21.890S	33	7.2	34O	
17	1981	1	30	176.274E	51.744N	33	7.0	16G	
18	1981	7	6	171.742E	22.293S	33	7.0	34O	
19	1981	7	15	167.601E	17.260S	30	7.0	33O	
20	1981	9	1	173.085W	14.960S	25	7.7	18Y	
21	1981	10	16	73.074W	33.134S	33	7.2	1O	
*22	1981	10	25	102.084W	18.048N	33	7.3	13G	17O
23	1981	12	26	177.741W	29.934S	33	7.1	36G	
24	1982	1	11	124.358E	13.752N	46	7.1	26O	
25	1982	6	7	98.358W	16.558N	34	7.0	12G	
26	1982	8	5	165.931E	12.597S	31	7.1	32G	
27	1982	12	19	175.864W	24.133S	33	7.7	20Y	
28	1983	4	3	83.123W	8.717N	37	7.3	13O	
29	1983	10	4	70.563W	26.535S	15	7.3	2O	
30	1984	2	7	160.469E	10.012S	18	7.5	31G	
31	1984	3	24	148.192E	44.117N	44	7.0	19G	
32	1984	11	17	98.027E	0.197N	33	7.2	13R	
33	1984	12	28	163.460E	56.194N	33	7.0	17G	
34	1985	3	3	71.871W	33.135S	33	7.8	1O	
35	1985	4	9	71.618W	34.131S	38	7.2	1O	
36	1985	5	10	151.045E	5.599S	27	7.1	31O	
37	1985	7	3	152.828E	4.439S	33	7.2	32O	
38	1985	9	19	102.533W	18.190N	28	8.1	17O	
39	1985	9	21	101.647W	17.802N	31	7.6	13G	
40	1985	9	26	178.656W	34.693S	52	7.0	14P	
*41	1985	11	28	166.185E	13.987S	33	7.1	16Y	33G/-
42	1985	11	28	166.240E	14.043S	33	7.0	33G	
43	1985	12	21	166.516E	13.966S	43	7.3	33G	
44	1986	4	30	102.973W	18.404N	27	7.0	17O	
45	1986	5	7	174.776W	51.520N	33	7.7	16G	
46	1986	10	20	176.367W	28.117S	29	8.1	13P	
47	1986	11	14	121.574E	23.901N	34	7.8	11R	
*48	1987	2	8	147.689E	6.088S	55	7.4	14Y	29G/-
*49	1987	3	5	70.161W	24.388S	62	7.3	1R	4G/1R
50	1987	10	6	172.225W	17.940S	16	7.3	19Y	
51	1987	10	16	149.060E	6.266S	48	7.4	30O	
52	1988	2	24	124.616E	13.477N	24	7.0	26O	
53	1988	4	12	72.305W	17.192S	33	7.0	1R	
54	1988	8	10	160.819E	10.366S	34	7.4	31G	
55	1989	10	18	121.883W	37.036N	18	7.1	18O	
56	1989	10	27	162.350E	11.022S	24	7.0	31G	
57	1989	11	1	142.760E	39.837N	28	7.4	21O	
58	1989	12	15	126.729E	8.337N	24	7.3	26O	
59	1990	3	5	168.063E	18.318S	20	7.0	33O	

Table 1. (Continued).

Earth-quakes	Time			Coordinates		Depth (km)	M_S	MNSK Zone	Notes
	Year	Month	Day	Longitude	Latitude				
60	1990	3	25	84.808W	9.919N	22	7.0	9G	
61	1990	4	5	147.596E	15.125N	11	7.5	7P	
62	1990	6	14	121.899E	11.76N	18	7.1	26O	
63	1990	7	16	121.172E	15.679N	25	7.8	26O	
64	1990	11	6	169.871E	53.452N	24	7.0	2H	
*65	1991	4	22	83.073W	9.685N	10	7.6	13O	6O
66	1991	10	14	158.442E	9.094S	23	7.1	31G	
67	1991	12	22	151.021E	45.533N	24	7.4	19G	
68	1992	5	17	126.645E	7.239N	32	7.1	26O	
69	1992	5	17	126.762E	7.191N	33	7.5	26O	
70	1992	5	27	165.239E	11.122S	18	7.0	15Y	
71	1992	6	28	116.436W	34.201N	1	7.6	7R	
72	1992	9	2	87.340W	11.742N	44	7.2	15O	
73	1992	12	12	121.896E	8.480S	27	7.5	10P	
74	1993	3	6	164.181E	10.972S	20	7.1	15Y	
75	1993	6	8	157.829E	51.218N	70	7.3	18G	
76	1993	8	8	144.801E	12.982N	59	8.0	7P	
77	1993	9	10	92.645W	14.717N	34	7.3	11G	
78	1993	10	13	146.020E	5.889S	25	7.0	14Y	
79	1993	10	25	145.990E	5.909S	30	7.0	14Y	
80	1993	11	13	158.647E	51.934N	34	7.0	18G	
81	1994	2	12	169.361E	20.553S	27	7.1	34G	
82	1994	2	15	104.302E	4.967S	23	7.0	27O	
83	1994	6	2	112.835E	10.477S	18	7.2	10P	
84	1994	7	13	167.518E	16.620S	33	7.3	33O	
85	1994	9	1	125.680W	40.402N	10	7.0	18O	
86	1994	10	4	147.321E	43.773N	14	8.1	19G	
87	1994	10	9	147.916E	43.905N	33	7.1	19G	
88	1994	11	14	121.067E	13.525N	31	7.1	26O	
89	1994	12	28	143.419E	40.525N	26	7.5	19G	
90	1995	4	7	173.529W	15.199S	21	8.0	18Y	
91	1995	4	21	125.564E	11.925N	17	7.2	26O	
92	1995	4	21	125.580E	12.059N	20	7.3	26O	
93	1995	5	5	125.297E	12.626N	16	7.0	26O	
94	1995	7	3	177.589W	29.211S	35	7.2	36G	
95	1995	7	30	70.294W	23.340S	45	7.3	1R	
96	1995	8	16	154.178E	5.799S	30	7.8	30G	
97	1995	8	16	154.347E	5.771S	33	7.2	30G	
98	1995	9	14	98.597W	16.779N	23	7.2	12G	
99	1995	10	9	104.205W	19.055N	33	7.4	17O	
100	1995	12	3	149.300E	44.663N	33	7.9	19G	
101	1996	2	7	149.909E	45.321N	33	7.0	19G	
102	1996	4	29	154.999E	6.518S	44	7.5	30G	
103	1996	6	10	177.632W	51.564N	33	7.6	16G	
104	1996	6	10	176.847W	51.478N	26	7.1	16G	
105	1996	6	11	125.154E	12.614N	33	7.0	26O	
106	1996	8	2	161.445E	10.769S	33	7.1	31G	
107	1996	11	12	75.668W	15.013S	33	7.3	3O	
108	1997	4	21	166.676E	12.584S	33	7.9	16Y	
109	1997	9	20	177.624W	28.683S	30	7.0	13P	
110	1997	12	5	162.035E	54.841N	33	7.6	20O	
111	1998	7	17	141.926E	2.961S	10	7.1	29O	
112	1998	8	4	80.393W	0.593S	33	7.1	2P	

Time limits are from June 1, 1978, to December 31, 1998. Only earthquakes that fall into one of zones defined by *MNSK* [1979] are listed. An asterisk (*) denotes an event for which the present zone assignment differs from that of *Kagan and Jackson* [1991].

Table 2. Number of earthquake epicenters in different MNSK[1979] regions.
(a) Magnitude≥7.0, June 1, 1978 – December 31,1998.

Color	Number of Zones (Z)	Average Zone Area (1000km^2)	PDE M_s		PDE M_0		CMT M_w		Average		Ratio	
			q	*f*	*q*	*f*	*q*	*f*	*q*	*f*	*q/Z*	*f/Z*
R	17	127	7	4	5	5	8	5	6.7	4.7	0.39	0.28
O	34	107	40	19	39	15	38	19	39.0	17.7	1.15	0.52
G	36	105	42	15	36	14	44	18	40.7	15.7	1.13	0.44
Y	21	127	13	7	17	8	14	9	14.7	8.0	0.70	0.38
H	3	203	1	1	0	0	1	1	0.67	0.67	0.22	0.22
P	14	283	9	6	8	5	11	7	9.3	6.0	0.66	0.43

(b) Magnitude≥7.5, June 1, 1978 – December 31,1998.

Color	Number of Zones (Z)	Average Zone Area (1000km^2)	PDE M_s		PDE M_0		CMT M_w		Average		Ratio	
			q	*f*	*q*	*f*	*q*	*f*	*q*	*f*	*q/Z*	*f/Z*
R	17	127	2	2	1	1	2	2	1.7	1.7	0.10	0.10
O	34	107	8	7	8	5	12	11	9.3	7.7	0.27	0.23
G	36	105	13	8	11	9	16	11	13.3	9.3	0.37	0.26
Y	21	127	4	3	3	2	2	2	3.0	2.3	0.14	0.11
H	3	203	0	0	0	0	0	0	0	0	0	0
P	14	283	4	3	3	3	4	3	3.7	3.0	0.26	0.21

q is the number of earthquakes. *f* is the number of zones filled by earthquakes.
Area represents the average area of one zone.
* abbreviations as follows: R, “red”; O, “orange”; Y, “yellow”; H, “hatched”; P, “purple” ; G, “green”;

Table 3. Earthquake Probabilities for Zones Specified by Nishenko [1991].

Num-ber	Zone	M_c	M_g	Md	Nishenko 10 years Probability	M_c			M_c-0.5		
						P Pr.	p	c	P Pr.	p	c
1	c1	7.7	7.7	H	.110	2.0E-5	0	0	6.0E-5	0	0
2	c3	9.4	7.7	H	.005	2.0E-4	0	0	8.0E-4	0	0
3	c4	7.9	7.7	H	.030	.0254	0	0	.0792	0	0
4	c5	8.0	7.7	H	.005	.0396	0	0	.1226	0	0
5	c5a	7.5	7.7	H	.330	.0195	0	0	.0610	0	0
6	c6	8.2	7.7	H	.240	.0132	0	0	.0412	0	0
7	c7	8.5	7.7	H	.040	.0094	0	0	.0292	0	0
8	c8	7.3	7.7	H	.005	.1269	0	0	.3716	0	0
9	c10	9.0	7.7	H	.200	.0030	0	0	.0094	0	0
10	p1	9.0	7.7	H	.100	.0016	0	0	.0052	0	0
11	p2	7.8	7.7	H	.130	.0052	0	0	.0165	0	0
12	p3	8.2	7.7	H	.005	.0014	0	0	.0042	0	1
13	p4a	8.0	7.7	H	.005	6.0E-4	0	0	.0016	0	0
14	p4b	8.0	7.7	H	.280	6.0E-4	0	0	.0020	0	0
15	p5	8.1	7.7	H	.040	.0010	0	0	.0034	0	0
16	ec1	7.9	7.7	H	.570	.0102	0	0	.0321	0	0
17	ec2	7.8	7.7	H	.190	.0074	0	0	.0231	0	0
18	ec3	7.7	7.7	H	.005	.0282	0	0	.0878	0	0
19	cr1	7.5	7.0	H	.310	.0219	0	0	.0684	0	0
20	cr2	7.3	7.0	H	.640	.0240	0	1	.0749	1	1
21	cr3	7.0	7.0	H	.080	.0755	0	0	.2288	0	0
22	cr4	7.3	7.0	H	.005	.0443	0	0	.1368	0	0
23	g1	7.5	7.0	G	.005	.0110	0	0	.0345	0	0
24	g2/3	7.3	7.0	H	.160	.0312	0	0	.0966	0	0
25	g4	7.4	7.0	H	.050	.0451	0	0	.1390	0	0
26	g5	7.9	7.0	H	.230	.0066	0	0	.0205	0	0
27	g6	7.9	7.0	H	.130	.0106	0	0	.0333	0	0
28	m1	7.8	7.0	H	.020	.0278	0	0	.0868	1	0
29	m3	7.8	7.0	H	.350	.0146	0	0	.0453	0	0
30	m4	7.8	7.0	H	.005	.0074	0	0	.0229	0	0
31	m5	7.8	7.0	H	.450	.0054	0	0	.0173	0	0
32	m6	7.4	7.0	H	.210	.0225	0	0	.0699	1	1
33	m7	7.3	7.0	H	.470	.0347	0	1	.1073	0	1
34	m8	7.7	7.0	H	.130	.0139	0	0	.0437	0	0
35	m9	7.8	7.0	D	.300	.0136	0	0	.0427	0	0
36	m10	7.6	7.0	H	.030	.0240	0	0	.0749	0	0
37	m11	8.1	7.0	H	.005	.0104	0	0	.0327	0	0
38	m12	7.5	7.0	H	.250	.0217	0	0	.0674	0	0
39	m14	8.2	7.0	D	.100	.0042	0	0	.0134	0	1
40	sa1	8.0	7.0	D	.005	.0064	0	0	.0203	0	0
41	sa2/3	6.5	7.0	D	.190	.0628	1	1	.1914	1	1
42	sa5	6.0	7.0	H	.930	.1177	0	0	.3470	0	0
43	sa6	7.0	7.0	D	.110	.0086	0	0	.0268	0	0
44	sa7	8.0	7.0	D	.010	.0030	0	0	.0098	0	0
45	sa8	7.5	7.0	D	.110	.0080	0	0	.0252	0	0
46	sa9	7.5	7.0	D	.080	.0070	1	0	.0223	1	0
47	sa10	7.5	7.0	G	.140	.0189	0	0	.0593	0	0
48	wo1	8.0	7.0	G	.005	8.0E-4	0	0	.0024	0	0
49	qc2	8.1	7.0	D	.040	.0010	0	0	.0030	0	0
50	qc3	7.3	7.0	H	.020	.0038	0	0	.0122	0	0
51	qc4	8.2	7.0	D	.040	.0030	0	0	.0094	0	0

Table 3. (Continued)

Number	Zone	M_c	M_g	Md	Nishenko 10 years Probability	M_c			M_c-0.5		
						P Pr.	p	c	P Pr.	p	c
52	qc5	8.0	7.0	D	.190	.0060	0	0	.0191	0	0
53	qc6	8.0	7.0	D	.210	.0137	0	0	.0431	0	0
54	qc7	9.2	7.0	D	.005	.0012	0	0	.0038	0	0
55	qc8	8.0	7.0	H	.160	.0118	0	0	.0371	0	0
56	qc9	8.0	7.0	H	.180	.0205	0	0	.0641	0	0
57	qc10	7.4	7.0	H	.480	.0603	0	0	.1842	0	0
58	qc11	7.4	7.0	H	.490	.0382	0	0	.1181	0	1
59	qc12	7.4	7.0	H	.440	.1945	0	0	.5430	0	0
60	qc13	8.0	7.0	H	.005	.0355	0	0	.1100	0	0
61	qc14'	7.4	7.0	H	.720	.0872	1	1	.2619	1	1
62	qc14"	7.4	7.0	H	.130	.0126	0	0	.0396	0	0
63	qc15	8.0	7.0	H	.040	.0396	0	0	.1222	0	0
64	kk1	7.5	7.7	H	.230	.0250	0	0	.0782	0	0
65	kk2	8.3	7.7	H	.030	.0068	0	0	.0217	0	0
66	kk3	9.0	7.7	H	.005	.0016	0	0	.0052	0	0
67	kk4	8.0	7.7	D	.200	.0118	0	0	.0373	0	0
68	kk6	8.5	7.7	H	.210	.0054	0	0	.0171	0	0
69	kk7	8.5	7.7	H	.005	.0054	0	0	.0167	0	0
70	kk8	7.6	7.7	D	.005	.0738	1	0	.2235	1	0
71	kk9	8.2	7.7	D	.005	.0171	0	1	.0538	1	1
72	j1	7.8	7.7	H	.005	.0221	0	0	.0692	0	0
73	j2	8.1	7.7	H	.005	.0139	0	0	.0441	0	0
74	j3	8.2	7.7	H	.005	.0092	0	0	.0286	0	1
75	j4	7.6	7.7	HD	.140	.0605	0	0	.1848	1	0
76	j5	7.4	7.7	H	.005	.0417	0	0	.1289	0	0
77	j6	7.4	7.7	H	.004	.1179	0	0	.3478	0	0
78	j6c	7.4	7.7	H	.001	.0353	0	0	.1096	0	0
79	j7	7.5	7.7	H	.005	.1026	0	0	.3056	0	0
80	j8	7.9	7.7	GD	.005	.0088	0	0	.0278	0	0
81	j9	8.4	7.7	H	.240	.0020	0	0	.0062	0	0
82	j10	8.1	7.7	H	.005	.0038	0	0	.0122	0	0
83	j11	8.1	7.7	H	.005	.0024	0	0	.0076	0	0
84	nb1	7.9	7.0	H	.580	.0828	0	0	.2493	0	0
85	nb2	7.7	7.0	H	.590	.1401	0	0	.4069	0	0
86	s1	7.8	7.0	H	.530	.0657	0	0	.1999	0	1
87	s2	7.8	7.0	H	.100	.0453	1	0	.1397	2	0
88	s5	7.5	7.0	H	.450	.1224	0	0	.3598	0	0
89	s6	8.0	7.0	H	.450	.0382	0	0	.1181	0	0
90	va1a	8.1	7.0	H	.480	.0247	0	0	.0769	0	0
91	va1b'	7.5	7.0	H	.800	.0327	0	0	.1017	0	0
92	va1b"	7.5	7.0	H	.030	.0414	0	0	.1276	0	0
93	va3	7.5	7.0	G	.005	.1085	0	0	.3219	0	0
94	va4	7.1	7.0	H	.600	.1412	0	0	.4096	1	0
95	va4c	7.5	7.0	G	.005	.0998	0	0	.2974	1	1
96	va6	7.2	7.0	H	.220	.2145	0	0	.5900	0	0
97	tk3	7.8	7.0	H	.580	.0343	0	0	.1066	0	0
98	tk5	7.7	7.0	H	.005	.0500	0	0	.1538	0	0
Sum					17.490	3.335	5	5	10.009	13	12

M_c,characteristic magnitude; M_g,generic magnitude for large earthquakes; “P Pr”,Poisson probability; “md”,method; “P”,PDE catalog; “c”,CMT catalog.

Table 4. List of Eligible Earthquakes in Zones Specified by Nishenko [1991].
(***a***) PDE Catalog, January 1,1989 - December 31, 1998.

Number	Date	Coordinates	Depth (km)	M_s	Zone	M_c	10-Year Probability %
1	Oct. 18, 1989	37.0N, 121.9W	19	*7.1	SA-2/SA-3	(7.0)/(6.5)	(5-15)/(9)
2	Nov. 1, 1989	39.8N, 142.8E	29	†7.4	J-4	7.6	7-21
3	Feb. 19, 1990	15.5S, 166.4E	12	†6.7	VA-4	7.1	60
4	Mar. 25, 1990	9.9N, 84.8W	22	†7.0	CR-2	7.3	64
5	Jun. 28, 1992	34.2N, 116.4W	1	*7.6	SA-9	(7.5)	(8)
6	Sep. 10, 1993	14.7N, 92.6W	34	†7.3	M-1	(7.8)	2
7	Jul. 13, 1994	16.6S, 167.5E	33	†7.3	VA-4c	7.5	≤1
8	Oct. 4, 1994	43.8N, 147.3E	14	†8.1	KK-9	8.2	≤1
9	Aug. 16, 1995	5.8S, 154.2E	30	*7.8	S-2	7.8	10
10	Dec. 3, 1995	44.8N, 150.2E	33	*7.9	KK-8	8.3/7.6	≤1
11	Feb. 25, 1996	16.2N, 98.0W	21	†6.9	M-6	7.4	21
12	Apr. 29, 1996	6.5S, 155.0E	44	†7.5	S-2	7.8	10
13	Jun. 10, 1996	51.6N, 177.6W	26	*7.6	QCAA-14’	(7.4)	(85)

(***b***) Harvard CMT Catalog, January 1,1989 - December 31, 1998.

Number	Date	Coordinates	Depth (km)	M_w	Zone	M_c	10-Year Probability %
1	Oct. 18, 1989	37.1N, 121.6W	19	*6.92	SA-2/SA-3	(7.0)/(6.5)	(5-15)/(9)
2	Mar. 25, 1990	10.0N, 84.6W	18	*7.33	CR-2	7.3	64
3	May 30, 1991	54.4N, 161.6E	24	†6.96	QCAA-11	(7.4)	(43-55)
4	Jul. 13, 1994	16.5S, 167.4E	25	†7.18	VA-4c	7.5	≤1
5	Oct. 4, 1994	43.6N, 147.6E	68	*8.29	KK-9	8.2	≤1
6	Dec. 28, 1994	40.6N, 143.0E	28	†7.76	J-3	8.2	≤1
7	Aug. 16, 1995	5.5S, 153.6E	46	†7.74	S-1	7.8	53
8	Sep. 14, 1995	16.7N, 98.5W	22	*7.38	M-7	7.3	47
9	Oct. 9, 1995	19.3N, 104.8W	15	†8.01	M-14	8.2	2-18
10	Feb. 25, 1996	15.9N, 98.0W	15	†7.13	M-6	7.4	21
11	Jun. 10, 1996	51.1N, 177.4W	29	*7.91	QCAA-14’	(7.4)	(85)
12	Nov. 12, 1996	15.0S, 75.4W	37	†7.74	P-3	8.2	≤1

* Earthquakes with magnitude greater than or equal to characteristic earthquake magnitude (M_c).

† Earthquakes with magnitude greater than or equal to M_c-0.5 but less than M_c.

Table 5. Summary of Hypothesis Testing for New Seismic Gap Model [Nishenko, 1991]: Probability {Random Score < Catalog Score}

Test	Catalog	P(Gap)	P(Poisson)
		M_c	
N	PDE	.000*	.791
	CMT	.000*	.791
L	PDE	.162	.068
	CMT	.495	.056
R	PDE	.000**	.803
	CMT	.000**	.974
		M_c -0.5	
N	PDE	.120	.800
	CMT	.075	.708
L	PDE	.000**	.033**
	CMT	.000**	.003**
R	PDE	.000**	.610
	CMT	.000**	.959

* Rejected at 95% confidence in two-tailed test (acceptance region 0.025-0.975).

** Rejected at 95% confidence in one-tailed test (acceptance region 0.05-1.00).