# Scoring annual earthquake predictions in China

Jiancang Zhuang[a], Chang-Sheng Jiang[b]

[a] *Institute of Statistical Mathematics*
*10-3 Midori-cho, Tachikawa, Tokyo 190-8562, Japan*
[b] *Institute of Geophysics, China Earthquake Administration*
*No.5 Minzu Daxue Nan Road, Haidian District, Beijing 100086, China*

**Abstract**

The Annual Consultation Meeting on Earthquake Tendency in China is held by the China Earthquake Administration (CEA) in order to provide one-year earthquake predictions over most China. In these predictions, regions of concern are denoted together with the corresponding magnitude range of the largest earthquake expected during the next year. Evaluating the performance of these earthquake predictions is rather difficult, especially for regions that are of no concern, because they are made on arbitrary regions with flexible magnitude ranges. In the present study, the gambling score is used to evaluate the performance of these earthquake predictions. Based on a reference model, this scoring method rewards successful predictions and penalizes failures according to the risk (probability of being failure) that the predictors have taken. Using the Poisson model, which is spatially inhomogeneous and temporally stationary, with the Gutenberg-Richter law for earthquake magnitudes as the reference model, we evaluate the CEA predictions based on 1) a partial score for evaluating whether issuing the alarmed regions is based on information that differs from the reference model (knowledge of average seismicity level) and 2) a complete score that evaluates whether the overall performance of the prediction is better than the reference model. The predictions made by the Annual Consultation Meetings on Earthquake Tendency from 1990 to 2003 are found to include significant precursory information, but the overall performance is close to that of the reference model.

*Keywords:* earthquake prediction, gambling score, Annual Consultation Meeting on Earthquake Tendency in China, point process

## 1. Introduction

During last 50 years, in numerous regions around the world (including China), earthquakes have caused enormous damage to both property and human life. For example, approximately 240,000 people lost their lives as a result of the $M7.8$ Tangshang earthquake, which occurred on July 28, 1976, and approximately 160,000 people were seriously injured. More recently, the $M8.0$ Wenchuan earthquake, which occurred on May 20, 2008 in a populated area in Sichuan Province, China, resulted in the loss of more than 70,000 lives. In China, preventing earthquake disasters and reducing their impact is an important task for both scientists and the government. The China Earthquake Administration (CEA), which was previously referred to as the State Seismological Bureau as well as the China Seismological Bureau, is a governmental agency that is dedicated to monitoring precursors of earthquakes and predicting the occurrence of earthquakes. The purpose of the Annual Consulting Meeting on Earthquake Tendency in China held each year by the CEA is to evaluate earthquake risk for most of the country for the coming year. By consensus of experts from the CEA institutes and provincial or municipal seismological bureaus, one-year predictions are made based on data from various observations, including seismicity parameters, deformation, apparent electric resistivity, underground water, stress, gravity field, and magnetic field. The findings of this meeting are published in a report called "The Annual Report of Earthquake Tendency" (Center for Analysis and Prediction, State Seismology Bureau, 1989, 1990, 1991, 1992, 1993, 1994, 1995, 1996, 1997; Center for Analysis and Prediction, China Earthquake Administration, 1998, 1999, 2000, 2001, 2002). In particular, a map of several alarmed regions is marked as having high probabilities of large earthquakes (usually $M \geqslant 5.5$ in the western part and $M \geqslant 5.0$ in the eastern part of China). These predictions are reported to the central and provincial governments for incorporation into disaster reduction policies, and are only made available to the public after a period of one year, because the government is the only legal authority able to perform mitigation actions. Details on earthquake prediction in China have been reported by Mei et al. (1993), Wu (1997), Wu et al. (2007) and Bormann (2011).

However, in the following year, earthquakes of expected magnitudes occur in some of these alarmed regions, as well as in unmarked regions, whereas no expected earthquakes occur in the other alarmed regions. An important issue arises regarding how to evaluate the prediction performance of the Annual Consultation Meeting. Shi et al. (2001), denoted hereinafter as SLZ, evaluated the prediction performance of the 1990-1998 reports using the R score and found that the CEA annual predictions were marginally better than background-based random predictions. They, concluded that the CEA predictions were still empirical and were in a preliminary stage of development.

The present study attempts to verify the results of SLZ using the gambling score, as proposed by Zhuang (2010). Zechar and Zhuang (2010) used this method to evaluate the significance of the predictions by Shebalin et al., using the reverse tracing of precursor (RTP ) algorithm (see, Shebalin et al., 2000, 2004, for details regarding the RTP algorithm). Molchan and Romashkova (2011) applied the RTP algorithm to evaluate the prediction performance of the M8 algorithm. In the present study, for different testing purposes, we apply the gambling score 1) for discrete bets, which are only on the alarmed regions, and 2) for bets in the continuous space-time, using the extension of the gambling score to the point process cases. The first application evaluates whether the predictions contain useful information that is not included in the reference model. That is to say, if the predictor knows something better than the reference model, he can always win if he uses a suitable betting strategy to decide whether to bet. In the second scoring method, the predictor is always required to bet under every situations. In other words, the first scoring method is for gamblers, namely, the partial score, and the second scoring method is for decision makers, namely, the complete score.

## 2. Evaluation methods

### *2.1. The R score*

The CEA annual predictions are statements on the occurrence of a future earthquake within a specific space-time-magnitude window (see Figure 1). The performance of such predictions can be evaluated using the R score (also referred to as the Hanssen-Kuiper skill score, see, e.g., Shi et al., 2001; Harte and Vere-Jones, 2005). In the context of the contingency table, the R score is defined as the difference between the fraction of successful positive predictions and the fraction of unsuccessful negative predictions in a 2×2 contingency table:

$$R = \frac{a}{a+c} - \frac{b}{b+d} \tag{1}$$

where $a$ is the number of correct positive predictions, $b$ is the number of false alarms (wrong positive predictions), $c$ is the number of misses (wrong negative predictions), and $d$ is the number of correct negatives.

However, applying the R score to the CEA annual predictions is difficult for the following reasons:

(a) These predictions are announced for irregular regions of different sizes. Shi et al. divided the entirety of China into $0.5^\circ \times 0.5^\circ$ cells, and used each cell as an individual observation in the contingency table.

(b) These predictions are announced for different magnitude ranges. In the western part of China, the predicted magnitudes are usually $6\pm$ (5.5∼6.5) or 6.0∼7.0, and in the eastern part of China, the predicted magnitudes are 5.0∼6.0. In SLZ, a cut-off magnitude of 5.0 was used for all the alarmed cells to fit the requirements of the R score testing.

(c) Most importantly, seismicity activity rates differ from region to region. The probabilities of earthquake occurrences are not the same in different cells, which makes the R score inapplicable. In other words, the R score tests the predictions against a Poisson model, the rate of which is spatially homogeneous, where the nonhomogeneous Poisson model is more suitable for use as a null model. In order to address this problem, in addition to the R score for the CEA predictions, SLZ also calculated the R score for the nonhomogeneous Poisson model. The predictions based on the nonhomogeneous Poisson model were constructed in the following manner. With the total number of alarmed cells in each year fixed to the same value as in the CEA annual predictions, each cell was set an alarm by a probability proportional to the seismicity rate inside the cell. The difference between these two R scores was regarded as the difference between the CEA annual predictions and the nonhomogeneous Poisson model. However, a number of problems remain with regard to such a treatment, as will be discussed later herein.

### *2.2. The gambling score*

In the present study, we will use another risk-compensation method, referred to as the gambling score, proposed by Zhuang (2010), to score these predictions. This method considers the risk (probability of failure) that the predictor has taken in each prediction and rewards the success in a manner that is compatible with the risk. This method requires a reference model for seismicity, which is generally the Poisson model for usual cases or the Omori-Utsu formula for forecasting aftershocks. Suppose that the reference model provides a probability $p_0$ that at least one event will occur in the space-time-magnitude window of interest. From the viewpoint of the reference model, the risk taken by the predictor is $1 - p_0$ if the predictor provides a "Yes"-prediction or $p_0$ if the predictor provides a "No"-prediction. The predictor, which is similar to a gambler, bets 1 point of his professional reputation on "Yes" or "No" according to his prediction. If the predictor bets one reputation point on "Yes" and loses, then his number of reputation points is reduced by 1. If his prediction is successful, then the predictor keeps his bet and is rewarded

$$G = (1 - p_0)/p_0 \tag{2}$$

reputation points. The quantity $(1 - p_0)/p_0$ is the return (reward/bet) ratio for bets on "Yes", chosen such that, if the reference model is correct, then the expected return from the bet is 0. Zhuang (2010) showed that if the reference model is unbiased, a positive expected return for the predictor requires that the predictions should be correlated more to the unknown true model than to the reference model.

## 3. Extending the gambling score to point-process models

The gambling score can also be extended to the case of probability forecasts and a continuous case of point process models. In the continuous space-time scale, point process models specified by the conditional intensity function are naturally used for describing, investigating, and forecasting seismicity in a particular region. A space-time-magnitude point process can be regarded as a random object, which takes values among sequences in the form $\{(t_i, x_i, m_i) : i = \dots, -1, 0, 1, \dots\}$, where $t_i$, $x_i$, and $m_i$ are the temporal, spatial, and magnitude components, respectively. The number of events in a point process that fall within any bounded space-time-magnitude volume is required to be finite. Such models are naturally specified by a conditional intensity function $\lambda$ of time $t$, location $x$, and magnitude $m$, which satisfies the following (see, e.g., Daley and Vere-Jones (2003), Chapter 7):

$$\lambda(t, x, m)\, \mathrm{d}t\, \mathrm{d}x\, \mathrm{d}m \approx \Pr\left[N(\mathrm{d}t\, \mathrm{d}x\, \mathrm{d}m) \geqslant 1 \mid \mathcal{H}_t\right]. \tag{3}$$

where the notation $\mathcal{H}_t$ is a simplification of the history of the observation of the process up to, but not including, time $t$, i.e., the subset $\{(t_i, x_i, m_i) : t_i <$

$t\}$ of the point process $N$ consisting of the elements with $t_i < t$; $N(\mathrm{d}t\,\mathrm{d}x\,\mathrm{d}m)$ is the number of earthquake events that fall within the volume $\mathrm{d}t\,\mathrm{d}x\,\mathrm{d}m = [t, t+\mathrm{d}t) \times [x, x+\mathrm{d}x) \times [m, m+\mathrm{d}m)$. The probability that at least one event occurs in the space-time-magnitude window $[T_1, T_2] \times B \times M$ is

$$\begin{aligned} & \Pr\{N([T_1, T_2] \times B \times M) > 0 \mid \mathcal{H}_{T_1}\} \\ = \; & 1 - \exp\left[-\int_M \int_B \int_{T_1}^{T_2} \lambda(t, x, m)\,\mathrm{d}t\,\mathrm{d}x\,\mathrm{d}m\right]. \end{aligned} \tag{4}$$

where $B$ is the total space, $[T_1, T_2]$ is the time interval of interest, and $M$ is the magnitude range. A forecasting procedure based on simulations performed using the conditional intensity can be found in Vere-Jones (1998).

In the following, we fix $\lambda_0$ to be the conditional intensity functions of the baseline (reference) model. We assume that the bet for "Yes" has a density $\beta(t, x, m)$ on the space-time-magnitude window of interest, say $V = [0, T] \times S \times M$. Then, the bet on $\mathrm{d}t\,\mathrm{d}x\,\mathrm{d}m$ is $b(t, x, m)\,\mathrm{d}t\,\mathrm{d}x\,\mathrm{d}m$ and the reward-bet ratio is

$$\begin{aligned} & \frac{1 - \Pr\{N(\mathrm{d}t\,\mathrm{d}x\,\mathrm{d}m) \geqslant 1 \mid \mathcal{H}_t\}}{\Pr\{N(\mathrm{d}t\,\mathrm{d}x\,\mathrm{d}m) \geqslant 1 \mid \mathcal{H}_t\}} \\ \approx \; & \frac{1 - \lambda_0(t, x, m)\,\mathrm{d}t\,\mathrm{d}x\,\mathrm{d}m}{\lambda_0(t, x, m)\,\mathrm{d}t\,\mathrm{d}x\,\mathrm{d}m} \\ \approx \; & [\lambda_0(t)\,\mathrm{d}t\,\mathrm{d}x\,\mathrm{d}m]^{-1}, \end{aligned} \tag{5}$$

where $\lambda_0$ is the conditional intensity for the reference model. Thus, the return for a bet for "Yes" on $\mathrm{d}t\,\mathrm{d}x\,\mathrm{d}m$ is

$$\frac{\beta(t, x, m)}{\lambda_0(t, x, m)} N(\mathrm{d}t\,\mathrm{d}x\,\mathrm{d}m) - \beta(t, x, m)\,\mathrm{d}t\,\mathrm{d}x\,\mathrm{d}m. \tag{6}$$

By integrating the above quantity over $V$, the forecaster's profit from betting on $V$ can be expressed as

$$R(V) = \sum_{i:(t_i, x_i, m_i) \in N \cap V} \frac{\beta(t_i, x_i, m_i)}{\lambda_0(t_i, x_i, m_i)} - \iiint_V \beta(t, x, m)\,\mathrm{d}t\,\mathrm{d}x\,\mathrm{d}m. \tag{7}$$

It is proven that $R(V)$ has an expectation of zero if $\lambda_0$ is identical to the conditional intensity of the true model (see, e.g., Zhuang, 2006 or Zhuang, 2010, for justification). Here, we refer to Zhuang (2010) again for a discussion on the upper bound of the expectation of $R(V)$.

## 4. Data analysis

In this section, we evaluate the CEA annual predictions with two different approaches. In Analysis I, we assume that each alarmed region corresponds to a bet of one point with respect to the occurrence of an earthquake of a magnitude in the declared range. It is difficult to deal with the unalarmed region, because the predicted magnitudes differ from alarm region to alarm region, and it is not easy to determine predictions for this region. For simplification, in Analysis I, we take it as an NA-prediction (no comment available) and nothing is bet on it. More careful treatments of these unalarmed regions are provided in Analysis II, where we use of the extended gambling score for space-time point processes, and assume that a unit positive density is bet on the alarmed region and a unit negative density is bet on both the alarmed region and the unalarmed region. The second score provides penalties for unpredicted events as well as rewards for the unalarmed region in which no large earthquake occurs.

### *4.1. Data*

Figure 1 shows an example of the CEA annual predictions for 1996, together with the epicenter locations of earthquakes of magnitudes $M \geqslant 5.0$ occurring in the same year. All of the predictions from 1990 to 2003 are listed in Table 1 and marked as purple closed curves in Figure 2.

In the estimation of the reference model, we use the Chinese monthly catalog (http://www.csndmc.ac.cn/newweb/data.htm). This catalog is compiled according to the records of the Chinese national and local observation networks, and the magnitude scale is unified as $M_L$. It is believed that this catalog is complete for events of $M_L \geqslant 3.0$ from 1970. In this study, we use $M_L\,3.5$ as the magnitude threshold. The epicenter locations of earthquakes of $M_L \geqslant 3.5$ are marked as black dots in Figure 2. However, since the annual predictions are aimed at earthquakes of $M_S 5.0$ and greater for Eastern China, and of $M_S 5.5$ and greater for Western China, we use the Chinese historical earthquake catalog (Department of Earthquake Disaster Prevention, China Earthquake Administration, 1999) and the catalog of fast-report earthquakes to verify the predictions. Earthquakes that fit the prediction criteria are plotted as orange circles in Figure 2 and listed in Table 2.

Since $M_L$ is used as the magnitude scale in the catalog for estimating the reference model, while the magnitudes used for the prediction are $M_S$. Therefore, conversion between $M_S$ and $M_L$ is necessary. Here, we use the empirical relation between $M_S$ and $M_L$ obtained by Wang (2010),

$$M_S = 0.84M_L + 0.64. \tag{8}$$

*4.2. The reference model*

As discussed earlier, the key to evaluating the gambling score is to evaluate the reference probability in each alarmed region. Here, we use a Poisson model, the rate of which is constant with respect to time and is nonhomogeneous in space. The occurrence rate of events larger than the threshold magnitude, say, $M_L\,3.5$, is written as

$$\lambda_0(x, y, m) = f(m \mid x, y)\, \lambda_0(x, y), \tag{9}$$

where $f(m \mid x, y) = b(x, y)\, 10^{-b(x,y)(m-3.5)} \ln 10, \quad m \geqslant 3.5$, is the probability density form of the Gutenberg-Richter law, with the $b$-value being location-dependent, and $\lambda_0(x, y)$ is the spatial rate. In an alarmed region $S$, the reference probability that at least one event will occur in the magnitude range between $m_1$ and $m_2$, given by the reference model, is

$$p_0(S, m_1, m_2) = 1 - \exp\left[-T \iint_S \int_{m_1}^{m_2} f(m \mid x, y)\, \lambda_0(x, y)\, \mathrm{d}m\, \mathrm{d}x\, \mathrm{d}y\right] \tag{10}$$

where $T$ is the length of the prediction time interval. It is reasonable to assume that $b$ is constant with respect to $S$, denoted by $b(S)$, and the above equation can simplified as

$$p_0(S, m_1, m_2) = 1 - \exp\left\{-T\, \Lambda_0(S)\, \left[10^{-b(S)(m_1-m_0)} - 10^{-b(S)(m_2-m_0)}\right]\right\} \tag{11}$$

where $\Lambda_0(S) = \iint_S \lambda_0(x, y)\, \mathrm{d}x\, \mathrm{d}y$ is the total rate in unit time on $S$.

*4.3. Analysis I: the partial score – treating the CEA predictions as Yes-only predictions*

In Analysis I, we evaluate the performance of the annual predictions made by the CEA during the period from 1990 to 2003. We use the Poisson model together with the Gutenberg-Richter law as the reference model introduced in Section 4.2 to determine whether these predictions include precursory information other than the background seismicity. In the calculation, the occurrence rate $\Lambda_0$ in $S$ can be estimated through a direct counting method, which is the same as the maximum likelihood estimate, i.e.,

$$\hat{\Lambda}_0(S) = \frac{\#\text{ events of } M_L \geqslant 3.5 \text{ in } (S \times T_0)}{\text{length of } T_0}, \tag{12}$$

where $T_0$ is the interval from the beginning of the catalog to the year in which the prediction is made. The $b$-value can be estimated through the maximum likelihood estimate (MLE, see, e.g., Aki, 1965, or Utsu, 1965), i.e.,

$$\hat{b}_{M_L}(S) = \frac{\log_{10} \mathrm{e}}{(\bar{m} - 3.45)}, \tag{13}$$

where $\bar{m}$ is the average magnitude of events of magnitude $\geqslant 3.5$ in the space-time window $S \times T_0$. In the above equation, 3.45 is used instead of the magnitude threshold of 3.5 in order to remove the effect caused by rounding all of the magnitudes to one digit. Thus, the return ratio for $S$ can estimated by

$$\hat{G}(S) = \frac{1 - p_0(S, m_1, m_2)}{p_0(S, m_1, m_2)}, \tag{14}$$

where $m_1$ and $m_2$ are the lower and upper bounds of the predicted magnitude range, respectively, converted from $M_S$ to $M_L$ by using (8) .

The number of events in the each alarmed region before the prediction year and the estimated $b$-values are listed in Table 1 together with the reference probabilities and the reputation return for each prediction. Table 2 lists all of the target earthquakes of $M_S$5.0+ occurring in the eastern part and of $M_S$5.5+ in the western part from 1990 to 2003. Table 1 indicates that the overall score depends to a great degree on individual successes. Predictions #4 and #9 in 2000, #3 in 1993, #10 in 1996, and #8 in 1995 are successful bets over regions of low seismicity probabilities ($\leq$ 5%). These predictions dominate the scores in the corresponding years as well as the total score. Figure 3 shows the yearly reputation return of CEA from 1990 to 2003. The initial impression is that the overall score is significantly better than the reference Poisson model. However, the performance varies greatly from year to year. The best yearly scores are 163.395, 71.198, 70.761, and 39.140, which were obtained during 2000, 1993, 1995, and 1996, respectively, whereas the predictions in 1990, 1992, and 1999 were either complete or almost complete failures, which resulted in a lose of points to the reference model.

*Confidence levels of significance.* It is worthwhile to evaluate the confidence levels of the total reputation return under the reference model, which can be done through simulation. We assume that the occurrences of events in each considered space-duration-magnitude window are independent from other windows. The random distribution of the predictor's score under the reference model can be obtained using the following simulation algorithm.

*Simulation algorithm of the predictor's score under the reference model.*

Step 1. Generate $X_1$, $X_2$, $\cdots$, $X_n$, $(i = 1, 2, \cdots, n)$ taking values 1 and 0 with probabilities $p_i$ and $1 - p_i$, respectively, where $p_i$ is the reference probability for the $i$th prediction, and $n$ is the total number of predictions.

Step 2. Calculate and record the total reputation return to the CEA predictions in this simulation using the following equation:

$$R_{total} = \sum_{i=1}^{n} \left[ X_i \frac{1 - p_i}{p_i} - (1 - X_i) \right]. \tag{15}$$

Step 3. Repeat Steps 1 and 2 several times.

Through 1,000,000 simulations using the above algorithm, we first obtained the 0.1-confidence band for each individual year in Figure 3, and showing the significance of predictions in 1993, 1995, and 2000. The random distribution of the total reputation return under the reference model during the entire time period, as shown in Figure 4. The density of this empirical distribution has a maximum corresponding to a total return of approximately -23.5, a median of -10.5, and mean of -0.032 (which is sufficiently close to the theoretical value of zero). The p-value of the confidence level is 0.22%, which corresponds to the total return of 299.83. In both cases, the null hypothesis assumes that CEA predictions based on the knowledge of averaging past seismicity (Poisson model) can be rejected with a probability greater than 99%, implying that CEA predictions include some precursory information.

*Comparison with the results of SZL.* Theoretically, the annual predictions consist of two components: one is from the temporal average of the nonhomogeneous seismicity rate in the past and the other is based on precursory information. In Analysis I, the seismicity average level is included in the reference model. In this sense, our analysis differs from the study by SLZ. The first test conducted by SLZ examined the significance of the predictions with respect to a homogenous Poisson null model. In order to compare the CEA annual predictions to the nonhomogeneous Poisson model, SLZ fixed the total number of alarmed cells and then redistributed the alarms over all of the cells according to chances proportion to the seismicity rates in each cell. The R scores for both the CEA predictions and the relocated predictions were 0.184 and 0.150, respectively. They concluded that the CEA predictions are just marginally improved from the nonhomogeneous Poisson model. The difference of 0.034 between these two R scores not only contains wise points in the predictions that are not contained in the nonhomogeneous Poisson model, but also subtracts the smarter parts of the nonhomogeneous Poisson model than in the predictions. As illustrated in Figure 5(a), if A and B represent the parts of the predictions and the nonhomogeneous Poisson model, respectively, that are better than the homogeneous Poisson model, the gambling score evaluates the size of the green part of $A$, whereas SLZ evaluated the difference between the sizes of $A$ and $B$. Such a small improvement in the R score has two possible causes: (a) the CEA annual predictions consist primarily of the knowledge of the seismicity rate in the past and contain very little precursory information and (b) the CEA annual predictions include little knowledge of past seismicity activity but with a similar amount of precursory information as in the seismicity. In Table 1, there are six successful predictions among the 133 predictions with reference probabilities of less than 10% and 10 successful predictions with reference probabilities of greater than 10%. It appears that (b) is more likely to have caused the small improvement in the CEA predictions. Furthermore, a direct method by which to improve the R score from the nonhomogeneous Poisson model is to consider more information of the spatial distribution of seismicity rates in the CEA predictions, as illustrated in Figure 5(b).

Moreover, there are other causes for the reduction in the improvement in CEA predictions in the R score from the nonhomogeneous Poisson models, as listed as below:

(a) The second test of SLZ considered a temporally nonstationary and spatially nonhomogeneous Poisson model. The total number of cells differs from year to year, which implies that the CEA predictions regard the seismicity rate as nonstationary. Fixing the same total number of alarmed cells is equivalent to testing a nonstationary null model. This does not happen to the partial gambling score test, since the reference model is always explicitly specified as a stationary nonhomogeneous Poisson model.

(b) Figure 6 shows that all of the alarmed regions cover quite a large number of $0.5° \times 0.5°$ cells. The cells in each of the alarmed regions are connected to each other. When the alarmed cells in the eastern part are redistributed, these cells have high probabilities to be redistributed in the high seismicity in the western part and to capture some $M5.0 \sim 5.5$ events. $M5.0 \sim 5.5$ events are not considered in the CEA annual predictions for the western part, whereas in the test of SLZ, these $M5.0 \sim 5.5$ events were taken into consideration. Second, such a redistribution destroyed the connectivity between cells in one original alarmed region. A large alarmed region might be split into several small regions in the second test of SLZ on the significance of the nonhomogeneous Poisson model. If an alarmed region covers both active and aseismic areas, the cells on its active part may stay at the same location in the redistribution, whereas the cells on its aseismic part are relocated in other active areas with a higher probability of capturing $M \geqslant 5$ events. A more reasonable way to conduct this test is to fix the shape of each the alarmed region and then not only randomly relocate and rotate the region within the entire region according to the total seismicity rate that the region covers, but also to assign the region a new prediction year randomly selected from all years with equal probabilities.

In summary, when only positive predictions are considered, the gambling score becomes a partial score that only evaluates whether a prediction includes useful information that is different from the reference model. The results show that there is significant precursory information in the CEA predictions. However, the question remains as to whether the basis of the CEA prediction can be used as a standard for making decisions in all cases. We consider this problem in Analysis II.

### *4.4. Analysis II: the complete score – evaluating CEA prediction in a continuous space and time*

In Section 4.2, we only consider the partial score that is applied to only the alarmed regions and show that the predictions include significant precursory information with respect to the reference Poisson model. In this case, the partial gambling score only rewards the predictor when his predictions are better than those of the reference model but does not penalize the predictor when his predictions are worse. However, as a governmental institution, the CEA should take responsibility for the missed earthquakes that occur in the unalarmed regions. In this subsection, we consider evaluating these predictions by extending the gambling score to the cases of point processes, as given in Section 3. We assume that the betting density function is

$$\beta(t,x,y,m) = \begin{cases} 1, & \text{if } (t,x,y,m) \text{ is in the alarmed region;} \\ -1, & \text{if } (t,x,y,m) \text{ is not in the alarmed region.} \end{cases} \tag{16}$$

One valuable property of the above choice is that, based on (6), the penalty for missing an earthquake is the same as the reward for a successful alarm of an earthquake of the same magnitude at the same location. In addition, the larger the earthquake, the larger the corresponding penalty or reward.

Again, we use the inhomogeneous Poisson model in (9) as the reference model. Denote as $A_+$ and $A_-$ the alarmed and unalarmed parts, respectively, in a space-time-magnitude volume $A$. The total score in $A$ is:

$$\begin{aligned} R &= \sum_i \frac{\beta(t_i,x_i,y_i,m_i) I[(t_i,x_i,y_i,m_i) \in N \cap A]}{\lambda_0(t_i,x_i,y_i,m_i)} - \iiiint_A \beta(t,x,y,m)\, \mathrm{d}t\, \mathrm{d}x\, \mathrm{d}y\, \mathrm{d}m \\ &= \sum_i \frac{I[(t_i,x_i,y_i,m_i) \in N \cap A_+]}{\lambda_0(t_i,x_i,y_i,m_i)} - \sum_i \frac{I[(t_i,x_i,y_i,m_i) \in N \cap A_-]}{\lambda_0(t_i,x_i,y_i,m_i)} \\ &\quad - |A_+| + |A_-| \end{aligned} \tag{17}$$

where $|A_+|$ and $A_-$ are the volume of $A_+$ and $A_-$, respectively, and $N$ consists of all of the target earthquakes.

On the right-hand side of (17), the first term represents the rewards for earthquakes with alarms, and the second term represents the penalty of missed earthquakes. The third term is the cost for making positive predictions, and the fourth term represents the payoff from successful negative predictions on the unalarmed regions. We denote the first and the second summation terms by $R_+$ and $R_-$, respectively. It is easy to verify that, if the reference model is the true model, then $\mathbf{E}[R_+ - |A_+|] = \mathbf{E}[R_- - |A_-|] = 0$.

We use a variable kernel method (see, e.g., Zhuang et al., 2002; Zhuang, 2011) to estimate $\lambda_0$ at the locations of each target earthquake and use the magnitude of the nearest 200 earthquakes of $M_L 3.5+$ to estimate the $b$-value at each location, both based on the catalog before the end of the year which is prior to the occurrence of the target earthquake, as shown in Table 2.

In the calculation, as shown in Figure 2, we first divide the target region into two parts: the western part and the eastern part. As mentioned in Section 1, the magnitude range for the western part is $M_S 5.5 \sim 9.0$ and that for the eastern part $M_S 5.0 \sim 8.5$. Second, we redefine the magnitude range of all of the alarms. We regard the lower bounds of the magnitude range as $M_S 5.5$ in the western part and $M_S 5.0$ in the eastern part. This is because the magnitude ranges in the CEA predictions are for the biggest events in each region in the next year. The results are listed in Table 3, which indicates the following:

(a) The total score is positive, i.e., 3,708.8 points gained from bets on a total space-time-magnitude volume of 33,585.3 (yr·deg$^2$·mag). However, this score is not significant. A big portion of this score is gained from betting "No" for great earthquakes ($M_S \geqslant 8.0$) in the non-alarmed regions. If the upper bounds for both the western part and the eastern part are lowered by 0.5, i.e., $M_S 5.5 \sim 8.5$ as the magnitude range for the western part and $M_S 5.0 \sim 8.0$ as the magnitude range for the eastern part, then the total score becomes $-1,089.1$ from bets on a total space-time-magnitude volume of 28,787.4 (yr·deg$^2$·mag). The total score changes from positive to negative when we lower the upper bound of the target magnitude range by 0.5, implying that the overall performance of the CEA predictions is similar to that of the reference models,

(b) The total gain from correctly predicted earthquakes in the alarmed regions is 2,469.3 at a cost of 605.5. The ratio of the gain to the cost is approximately 4.08, which is much higher than the expected value of 1, implying that the alarmed regions are selected based on skills that are more advanced than the reference model. Thus, the conclusions for Analysis I are confirmed.

In summary, the CEA predictions are significantly better in selecting certain regions with certain skills, as compared to the reference model (knowledge of seismicity activity level), whereas the overall performance is marginal. These results also confirm the conclusions of SLZ.

## 5. Conclusions

In the present study, we have carried out tests on the CEA annual predictions with respect to the stationary nonhomogeneous Poisson model using the gambling scoring method in two steps. In Analysis I, one reputation point is taken from the predictor for each false alarm, and reputation points are rewarded for each successful alarm according to the reference model in a manner that compensates the risk taken by the predictors. The flexibility of the gambling score makes it more suitable and powerful than other available scoring methods in testing these CEA annual predictions, which are issued on irregular regions and different magnitude ranges. Using the partial score, where the predictions for the non-alarmed region are considered the same as by the the reference model, it is shown that the alarmed regions in the CEA annual predictions from 1990 to 2003 include significant precursory information that is not included in knowledge of the average seismicity level, even though the performance differs vastly from year to year. When both alarmed and unalarmed regions are considered in Analysis II, the results show that the average gain per unit space-time-magnitude volume in the alarmed region is higher than the average loss per unit space-time-magnitude volume in the unalarmed region while the total score is marginally positive. The results imply that, if the information of the spatial distribution of the seismicity activity is included, the CEA predictions can be significantly superior to the nonhomogeneous Poisson model in the R score test. In summary, the total score of the CEA predictions depends on how to deal with the predictions for the non-alarmed regions: if they are regarded as by the nonhomogeneous Poisson reference model (or NA-predictions), the CEA predictions are shown significantly to include precursory information; if the non-alarmed regions are considered as negative predictions, the performance of the CEA predictions is similar to the reference model.

## 6. Acknowledgements

The study is supported by Grant-in-Aid Nos 20240027 for Scientific Research (A), and 22700299 for Young Scientists (B), both from Ministry of Eduction, Science, Sports and Culture, Japan. The second author is also supported by No. 40804010 for Young Scientists, China National Natural Science Foundation. Helpful discussions with Prof. Zhongliang Wu from Institute of Geophysics, CEA, Prof. Yongxian Zhang from China Seismic Network Center, CEA, Dr. Matt Gerstenberger from GNS Sciences, New Zealand, Prof.

Mitsuhiro Matsu'ura and Prof. Yosihiko Ogata from the Institute of Statistical Mathematics, and Prof. David Vere-Jones from Victoria University of Wellington of New Zealand, are gratefully acknowledged. The authors also thank the editor and two anonymous reviewers for their encouragement and insights.

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Table 1: Scores for each CEA prediction. $N_{(M\geqslant 3.5)}$: number of earthquake of $M_L \geqslant 3.5$ in the prediction region. $b_{M_L}$: Gutenber-Richter $b$-value for the $M_L$ scale. $p_0$: reference probabilities. $G$: return ratio. $R$: reputation return.

| **Year** | **#** | **Region** | **Mag.** | $N_{(M_L\geqslant 3.5)}$ | $b_{M_L}$ | $p_0$ | $G$ | *Success?* | $R$ |
|---|---|---|---|---|---|---|---|---|---|
| 1990 | 01 | C Tianshan | 6.0-7.0 | 171 | 0.806 | 0.036 | 27.066 | 0 | -1.000 |
| | 02 | C Gansu | 6.0-7.0 | 70 | 0.828 | 0.013 | 77.074 | 0 | -1.000 |
| | 03 | NW Yunnan | 5.5-6.5 | 215 | 0.961 | 0.061 | 15.274 | 0 | -1.000 |
| | 04 | Kunming | 5.5-6.5 | 11 | 0.609 | 0.018 | 54.633 | 0 | -1.000 |
| | 05 | S Sichuan | 6.0-7.0 | 138 | 0.835 | 0.024 | 40.465 | 0 | -1.000 |
| | 06 | Tangshang | 5.0-6.0 | 16 | 0.604 | 0.060 | 15.700 | 0 | -1.000 |
| | 07 | Yellow Sea | 5.0-6.0 | 48 | 0.952 | 0.053 | 17.790 | 0 | -1.000 |
| 1991 | 01 | C Tianshan | 5.5-6.5 | 184 | 0.801 | 0.109 | 8.196 | 0 | -1.000 |
| | 02 | W to Urumqi | 6.0-7.0 | 137 | 0.878 | 0.017 | 56.590 | 0 | -1.000 |
| | 03 | C Gansu | 6.0-7.0 | 129 | 0.869 | 0.017 | 56.779 | 0 | -1.000 |
| | 04 | N to Yinchuan | 6.0-7.0 | 108 | 1.000 | 0.006 | 157.599 | 0 | -1.000 |
| | 05 | S Gansu | 5.5-6.5 | 84 | 0.975 | 0.022 | 45.055 | 0 | -1.000 |
| | 06 | S Shanxi | 5.0-6.0 | 63 | 0.948 | 0.067 | 13.947 | 0 | -1.000 |
| | 07 | W to Beijing | 5.0-6.0 | 70 | 0.647 | 0.200 | 4.000 | 1 | 4.000 |
| | 08 | W Liaoning | 5.0-6.0 | 22 | 1.137 | 0.012 | 83.112 | 0 | -1.000 |
| | 09 | Yellow Sea | 5.0-6.0 | 112 | 0.946 | 0.117 | 7.573 | 0 | -1.000 |
| | 10 | NW Yunnan | 5.5-6.5 | 161 | 1.019 | 0.033 | 29.077 | 0 | -1.000 |
| | 11 | N Yunnan & S. Sichuan | $\geqslant 6.0$ | 323 | 0.848 | 0.054 | 17.520 | 0 | -1.000 |
| 1992 | 01 | Kashi | 5.5-6.5 | 823 | 0.757 | 0.456 | 1.195 | 0 | -1.000 |
| | 02 | C Tianshan | 5.5-6.5 | 217 | 0.761 | 0.146 | 5.864 | 0 | -1.000 |
| | 03 | C. Gansu | 5.5-6.5 | 81 | 0.883 | 0.032 | 30.557 | 0 | -1.000 |
| | 04 | N. to Yinchuan | 6.0-7.0 | 92 | 0.963 | 0.007 | 152.441 | 0 | -1.000 |
| | 05 | Being to N Shanxi | 5.0-6.0 | 30 | 1.068 | 0.020 | 48.992 | 0 | -1.000 |
| | 06 | S. Gansu | 5.5-6.5 | 108 | 0.904 | 0.038 | 25.371 | 0 | -1.000 |
| | 07 | NW Yunnan | 5.5-6.5 | 317 | 0.952 | 0.085 | 10.765 | 0 | -1.000 |
| | 08 | N To Kunming | 6.0-7.0 | 224 | 0.851 | 0.032 | 30.299 | 0 | -1.000 |
| | 09 | Yellow Sea | 5.0-6.0 | 165 | 0.969 | 0.148 | 5.746 | 0 | -1.000 |
| 1993 | 01 | Kashi | 5.5-6.5 | 772 | 0.750 | 0.432 | 1.313 | 1 | 1.313 |
| | 02 | N Xiangqi | 6.0-7.0 | 189 | 0.908 | 0.018 | 54.474 | 0 | -1.000 |
| | 03 | C W Gansu | 6.0-7.0 | 132 | 0.887 | 0.014 | 68.313 | 1 | 68.313 |
| | 04 | N to Yinchuan | 5.5-6.5 | 106 | 0.906 | 0.035 | 27.401 | 0 | -1.000 |
| | 04 | Beijing | 4.5-5.5 | 106 | 0.676 | 0.507 | 0.973 | 0 | -1.000 |
| | 06 | Yellow Sea | 5.0-6.0 | 74 | 0.903 | 0.084 | 10.904 | 0 | -1.000 |
| | 07 | NW Yunnan | 5.5-6.5 | 754 | 0.766 | 0.400 | 1.501 | 0 | -1.000 |

(Continued on Next Page...)

(Continuation of Table 1)

| Year | # | Region | Mag. | $N_{(M\geqslant3.5)}$ | $b_{M_L}$ | $p_0$ | $G$ | *Success?* | $R$ |
|---|---|---|---|---|---|---|---|---|---|
| | 08 | SW Sichuan | 5.5-6.5 | 138 | 0.708 | 0.117 | 7.575 | 1 | 7.575 |
| | 09 | S Gansu | 5.5-6.5 | 62 | 0.951 | 0.017 | 59.388 | 0 | -1.000 |
| 1994 | 01 | Kashi | 5.5-6.5 | 652 | 0.689 | 0.458 | 1.182 | 1 | 1.182 |
| | 02 | W to Urumqi | 6.0-7.0 | 124 | 0.847 | 0.017 | 58.532 | 0 | -1.000 |
| | 03 | C Qinghai | 5.5-6.5 | 78 | 0.622 | 0.096 | 9.418 | 0 | -1.000 |
| | 04 | C Gansu | 5.5-6.5 | 32 | 0.790 | 0.018 | 53.562 | 0 | -1.000 |
| | 05 | NW Yunnan | 6.0-7.0 | 393 | 1.007 | 0.019 | 51.304 | 0 | -1.000 |
| | 06 | S Sichuan | 5.5-6.5 | 36 | 0.841 | 0.016 | 61.288 | 0 | -1.000 |
| | 07 | N Shanxi | 5.0-5.5 | 36 | 0.953 | 0.026 | 36.879 | 0 | -1.000 |
| | 08 | Yellow Sea | 5.0-6.0 | 41 | 0.850 | 0.055 | 17.234 | 0 | -1.000 |
| 1995 | 01 | Kashi | 5.5-6.5 | 1071 | 0.763 | 0.493 | 1.030 | 0 | -1.000 |
| | 02 | N Xinjiang | 5.5-6.5 | 214 | 0.897 | 0.067 | 13.856 | 1 | 13.856 |
| | 03 | C Qinghai | 5.5-6.5 | 75 | 0.636 | 0.084 | 10.967 | 0 | -1.000 |
| | 04 | C Gansu | 5.5-6.5 | 160 | 0.749 | 0.103 | 8.735 | 0 | -1.000 |
| | 05 | C S Shanxi | 5.0-6.0 | 52 | 0.967 | 0.054 | 17.405 | 0 | -1.000 |
| | 06 | Yellow Sea | 5.5-6.5 | 32 | 0.790 | 0.018 | 55.815 | 0 | -1.000 |
| | 07 | E Guangdong | 5.0-6.0 | 24 | 0.983 | 0.019 | 50.829 | 0 | -1.000 |
| | 08 | Leizhou Peninsula | 5.0-6.0 | 10 | 0.790 | 0.016 | 60.560 | 1 | 60.560 |
| | 09 | S Yunnan | 5.5-6.5 | 502 | 0.850 | 0.187 | 4.345 | 1 | 4.345 |
| | 10 | NW Yunnan | 6.0-7.0 | 398 | 0.891 | 0.039 | 24.954 | 0 | -1.000 |
| | 11 | Garze | 5.5-6.5 | 25 | 0.790 | 0.014 | 71.582 | 0 | -1.000 |
| 1996 | 01 | Kashi | 6.0-7.0 | 1368 | 0.761 | 0.257 | 2.894 | 1 | 2.894 |
| | 02 | N Xinjiang | 5.5-6.5 | 304 | 0.858 | 0.109 | 8.171 | 0 | -1.000 |
| | 03 | N Qinghai | 5.5-6.5 | 27 | 0.811 | 0.013 | 76.792 | 0 | -1.000 |
| | 04 | C. Gansu | 5.5-6.5 | 158 | 0.874 | 0.054 | 17.526 | 0 | -1.000 |
| | 05 | N. to Yinchuan | 5.5-6.5 | 104 | 1.015 | 0.018 | 55.175 | 0 | -1.000 |
| | 06 | NE Shanxi | 5.5-6.0 | 67 | 0.714 | 0.037 | 26.154 | 0 | -1.000 |
| | 07 | Bohai Sea | 5.0-6.0 | 77 | 1.168 | 0.030 | 32.594 | 0 | -1.000 |
| | 08 | Yellow Sea | 5.0-6.0 | 65 | 0.978 | 0.050 | 18.866 | 0 | -1.000 |
| | 09 | SE Qinghai | 5.5-6.5 | 79 | 0.933 | 0.020 | 48.056 | 0 | -1.000 |
| | 10 | C S Sichuan | 6.0-7.0 | 81 | 0.710 | 0.024 | 41.069 | 0 | -1.000 |
| | 11 | NW Yunnan | 6.0-7.0 | 331 | 0.955 | 0.021 | 47.246 | 1 | 47.246 |
| | 12 | S Yunnan | 5.5-6.5 | 441 | 0.795 | 0.205 | 3.880 | 0 | -1.000 |
| | 13 | Leizhou Peninsula | 5.0-6.0 | 30 | 0.547 | 0.101 | 8.903 | 0 | -1.000 |
| 1997 | 01 | Kashi | 5.5-6.5 | 816 | 0.752 | 0.396 | 1.524 | 0 | -1.000 |
| | 02 | C Tianshan | 5.5-6.5 | 155 | 0.799 | 0.073 | 12.654 | 0 | -1.000 |
| | 03 | Urumqi | 5.5-6.5 | 222 | 0.800 | 0.103 | 8.739 | 0 | -1.000 |
| | 04 | NW Qinghai | 5.5-6.5 | 86 | 0.731 | 0.057 | 16.504 | 0 | -1.000 |
| | 05 | C Gansu | 5.5-6.5 | 150 | 0.849 | 0.056 | 16.929 | 0 | -1.000 |
| | 06 | N to Yinchuan | 5.5-6.5 | 114 | 0.947 | 0.026 | 36.820 | 0 | -1.000 |
| | 07 | N Shanxi to NW Hebei | 5.0-6.0 | 92 | 0.705 | 0.171 | 4.847 | 0 | -1.000 |
| | 08 | Bohai Sea | 5.0-6.0 | 38 | 1.115 | 0.017 | 56.718 | 0 | -1.000 |
| | 09 | SE Qinghai | 5.5-6.5 | 119 | 0.960 | 0.026 | 37.349 | 0 | -1.000 |
| | 10 | C S Sichuan | 6.0-7.0 | 71 | 0.757 | 0.015 | 65.327 | 0 | -1.000 |
| | 11 | NW Yunnan | 5.5-6.5 | 419 | 0.905 | 0.115 | 7.731 | 0 | -1.000 |
| | 12 | S Yunnan | 5.5-6.5 | 313 | 0.840 | 0.118 | 7.478 | 1 | 7.478 |
| 1998 | 01 | Kashi | 5.5-6.5 | 1722 | 0.759 | 0.629 | 0.591 | 1 | 0.591 |
| | 02 | Urumqi | 5.5-6.5 | 144 | 0.828 | 0.057 | 16.465 | 0 | -1.000 |
| | 03 | C Qinghai | 5.5-6.5 | 83 | 0.582 | 0.105 | 8.557 | 0 | -1.000 |
| | 04 | C Gansu | 5.5-6.5 | 87 | 1.017 | 0.014 | 71.932 | 0 | -1.000 |
| | 05 | N to Yinchuan | 5.5-6.5 | 125 | 0.878 | 0.039 | 24.478 | 0 | -1.000 |
| | 06 | C Sichuan | 5.5-6.5 | 198 | 0.764 | 0.105 | 8.517 | 0 | -1.000 |
| | 07 | NW Yunnan | 6.0-7.0 | 392 | 0.954 | 0.023 | 42.613 | 0 | -1.000 |

(Continued on Next Page. . . )

(Continuation of Table 1)

| **Year** | **#** | **Region** | **Mag.** | $N_{(M\geqslant 3.5)}$ | $b_{M_L}$ | $p_0$ | $G$ | *Success?* | $R$ |
|---|---|---|---|---|---|---|---|---|---|
| | 08 | S Yunnan | 5.5-6.5 | 410 | 0.863 | 0.132 | 6.591 | 0 | -1.000 |
| | 09 | NW Hebei | 5.0-6.0 | 87 | 0.625 | 0.200 | 3.991 | 1 | 3.991 |
| | 10 | Bohai Sea | 5.0-6.0 | 74 | 1.033 | 0.044 | 21.951 | 0 | -1.000 |
| 1999 | 01 | Bohai Sea | 5.5-6.5 | 46 | 1.024 | 0.007 | 146.849 | 0 | -1.000 |
| | 02 | N. to Yinchuan | 5.5-6.5 | 93 | 0.967 | 0.018 | 54.065 | 0 | -1.000 |
| | 03 | W to Urumqi | 5.5-6.5 | 98 | 0.791 | 0.045 | 20.988 | 0 | -1.000 |
| | 04 | Kashi | 6.0-7.0 | 1558 | 0.757 | 0.266 | 2.763 | 0 | -1.000 |
| | 05 | S Sichuan | 6.0-7.0 | 119 | 1.016 | 0.005 | 219.555 | 0 | -1.000 |
| | 06 | NW Yunnan | 5.5-6.5 | 463 | 0.737 | 0.249 | 3.016 | 0 | -1.000 |
| | 07 | S Yunnan | 5.5-6.5 | 192 | 0.775 | 0.094 | 9.640 | 0 | -1.000 |
| | 08 | C Qinghai | 5.5-6.5 | 92 | 0.592 | 0.107 | 8.362 | 0 | -1.000 |
| | 09 | C Gansu | 5.5-6.5 | 69 | 1.039 | 0.009 | 105.099 | 0 | -1.000 |
| 2000 | 01 | N Shanxi | 5.0-6.0 | 82 | 0.668 | 0.157 | 5.384 | 0 | -1.000 |
| | 02 | Bohai Sea | 5.5-6.5 | 65 | 0.854 | 0.022 | 45.257 | 0 | -1.000 |
| | 03 | Leizhou Peninsula | 5.0-6.0 | 7 | 0.997 | 0.004 | 221.429 | 0 | -1.000 |
| | 04 | C Gansu | 5.5-6.5 | 69 | 1.032 | 0.009 | 104.834 | 1 | 104.834 |
| | 05 | W to Urumqi | 5.5-6.5 | 102 | 0.795 | 0.045 | 21.303 | 0 | -1.000 |
| | 06 | Kashi | 5.5-6.5 | 1369 | 0.745 | 0.546 | 0.833 | 0 | -1.000 |
| | 07 | N Sichuan | 5.5-6.5 | 253 | 0.891 | 0.068 | 13.618 | 0 | -1.000 |
| | 08 | C S Sichuan | 6.0-7.0 | 56 | 0.897 | 0.004 | 225.021 | 0 | -1.000 |
| | 09 | SE Qinghai | 6.0-7.0 | 82 | 0.766 | 0.015 | 66.561 | 1 | 66.561 |
| | 10 | NW Yunnan | 5.5-6.5 | 281 | 1.017 | 0.041 | 23.469 | 0 | -1.000 |
| 2001 | 01 | E to Hohhot | 5.0-6.0 | 102 | 0.677 | 0.180 | 4.546 | 0 | -1.000 |
| | 02 | Bohai Sea | 5.0-6.0 | 47 | 1.055 | 0.023 | 41.895 | 0 | -1.000 |
| | 03 | C Gansu | 5.5-6.5 | 170 | 0.861 | 0.052 | 18.256 | 0 | -1.000 |
| | 04 | N To Kunming | 5.5-6.5 | 130 | 0.852 | 0.042 | 22.843 | 0 | -1.000 |
| | 05 | W Yunnan | 5.5-6.5 | 743 | 0.767 | 0.311 | 2.217 | 1 | 2.217 |
| | 06 | Kashi | 6.0-7.0 | 982 | 0.769 | 0.156 | 5.405 | 0 | -1.000 |
| | 07 | Akesu | 5.5-6.5 | 328 | 0.657 | 0.243 | 3.123 | 0 | -1.000 |
| | 08 | Aba | 6.0-7.0 | 69 | 0.771 | 0.012 | 84.724 | 0 | -1.000 |
| 2002 | 01 | S Yunnan | 6.0-7.0 | 427 | 0.821 | 0.050 | 18.939 | 0 | -1.000 |
| | 02 | SE Qinghai & N Sichuan | 6.0-7.0 | 119 | 0.942 | 0.007 | 150.241 | 0 | -1.000 |
| | 03 | C Qinghai | 6.0-7.0 | 37 | 0.494 | 0.032 | 30.336 | 0 | -1.000 |
| | 04 | S Sichuan | 5.5-6.5 | 421 | 0.877 | 0.112 | 7.942 | 0 | -1.000 |
| | 05 | E to Hohhot | 5.0-6.0 | 51 | 0.685 | 0.090 | 10.153 | 0 | -1.000 |
| | 06 | Kashi | 5.5-6.5 | 1208 | 0.815 | 0.370 | 1.706 | 1 | 1.706 |
| | 07 | C Yunnan | 6.0-7.0 | 80 | 0.831 | 0.009 | 110.063 | 0 | -1.000 |
| | 08 | C Gansu | 5.5-6.5 | 169 | 0.849 | 0.053 | 17.803 | 0 | -1.000 |
| 2003 | 01 | Kashi | 6.0-7.0 | 2101 | 0.797 | 0.248 | 3.027 | 0 | -1.000 |
| | 02 | W to Urumqi | 5.5-6.5 | 214 | 0.848 | 0.065 | 14.333 | 0 | -1.000 |
| | 03 | NW Yunnan | 5.5-6.5 | 186 | 0.843 | 0.058 | 16.164 | 1 | 16.164 |
| | 04 | NE to Kunming | 5.5-6.5 | 153 | 0.855 | 0.046 | 20.938 | 0 | -1.000 |
| | 05 | Garze | 6.5-7.5 | 83 | 0.601 | 0.016 | 60.089 | 0 | -1.000 |
| | 06 | Aba | 5.5-6.5 | 87 | 0.950 | 0.016 | 60.450 | 0 | -1.000 |
| | 07 | C Gansu | 5.5-6.5 | 202 | 0.858 | 0.059 | 15.978 | 0 | -1.000 |
| | 08 | E to Hohhot | 5.0-6.0 | 117 | 0.751 | 0.153 | 5.530 | 0 | -1.000 |

Table 2: List of target earthquakes in the Chinese historical catalog. $\lambda$ and $b_{M_L}$ represent the seismicity rate of $M_L$3.5+ and the $b$-value for the $M_L$-scale at the epicentral location, respectively. In the Reg. collum, "W" represents Western China and "E" represents Eastern China. In the Remark column, the number corresponds the alarmed region in the same year which the earthquake falls in, and $<$ and $>$ mean, respectively, the earthquake is lower and higher than the predicted magnitude range.

| **Date** | **Time** | **Long.** | **Lat.** | **Mag.** | $\lambda$ | $b_{M_L}$ | **Reg.** | **Remark** |
|---|---|---|---|---|---|---|---|---|
| 1990/01/14 | 11:03 | 37.8 | 92.0 | 6.5 | 0.332 | 0.545 | W | |
| 1990/04/17 | 09:59 | 39.5 | 75.2 | 6.3 | 20.015 | 0.744 | W | |
| 1990/04/26 | 17:37 | 36.1 | 100.3 | 7.0 | 0.168 | 0.862 | W | |
| 1990/05/07 | 13:17 | 36.1 | 100.4 | 5.5 | 0.092 | 0.855 | W | |
| 1990/10/20 | 16:07 | 37.1 | 103.7 | 6.1 | 3.590 | 0.916 | W | |
| 1991/01/29 | 06:28 | 38.4 | 112.6 | 5.1 | 0.424 | 0.835 | E | |
| 1991/02/25 | 22:30 | 40.4 | 79.4 | 6.5 | 1.049 | 0.682 | W | |
| 1991/03/26 | 02:02 | 40.0 | 113.8 | 5.8 | 29.150 | 0.800 | E | #7 |
| 1991/05/30 | 07:06 | 39.5 | 118.2 | 5.1 | 111.644 | 0.471 | E | |
| 1991/09/30 | 09:15 | 43.3 | 112.4 | 5.4 | 0.158 | 0.753 | E | |
| 1992/01/23 | 05:41 | 35.3 | 121.2 | 5.3 | 0.050 | 0.955 | E | |
| 1992/02/18 | 19:16 | 25.0 | 119.8 | 5.2 | 0.150 | 0.476 | E | |
| 1993/01/27 | 04:32 | 23.1 | 101.1 | 6.3 | 28.148 | 0.840 | W | |
| 1993/07/17 | 17:46 | 27.9 | 99.6 | 5.6 | 1.497 | 0.724 | W | #8 |
| 1993/08/14 | 22:29 | 25.5 | 101.3 | 5.5 | 0.882 | 0.996 | W | |
| 1993/10/02 | 16:42 | 38.2 | 88.9 | 6.6 | 0.477 | 0.545 | W | |
| 1993/10/02 | 17:43 | 38.2 | 88.6 | 5.5 | 0.130 | 0.550 | W | |
| 1993/10/03 | 01:23 | 38.1 | 88.6 | 5.5 | 0.146 | 0.546 | W | |
| 1993/10/26 | 19:38 | 38.6 | 98.7 | 6.0 | 1.434 | 0.793 | W | #3 |
| 1993/12/01 | 04:37 | 39.4 | 75.4 | 6.0 | 85.560 | 0.749 | W | #1 |
| 1994/01/03 | 13:52 | 36.1 | 100.1 | 6.0 | 9.769 | 0.742 | W | |
| 1994/01/12 | 18:22 | 39.4 | 75.7 | 5.6 | 3.522 | 0.728 | W | #1 |
| 1994/02/16 | 15:09 | 36.2 | 100.2 | 5.8 | 3.378 | 0.742 | W | |
| 1994/09/24 | 03:15 | 36.2 | 100.3 | 5.5 | 2.533 | 0.745 | W | |

(Continued on Next Page...)

(Continuation of Table 2)

| Date | Time | Long. | Lat. | Mag. | $\lambda$ | $b_{M_L}$ | Reg. | Remark |
|---|---|---|---|---|---|---|---|---|
| 1994/12/30 | 02:58 | 28.9 | 103.6 | 5.7 | 21.022 | 0.771 | W | |
| 1994/12/31 | 10:57 | 21.0 | 109.4 | 6.1 | 0.053 | 0.957 | E | |
| 1995/01/10 | 18:09 | 20.5 | 109.4 | 6.2 | 1.005 | 0.950 | E | #8> |
| 1995/02/25 | 11:15 | 24.5 | 118.6 | 5.3 | 0.248 | 0.665 | E | |
| 1995/03/23 | 14:14 | 20.0 | 109.3 | 5.1 | 0.044 | 0.937 | E | |
| 1995/04/25 | 00:13 | 22.8 | 103.1 | 5.6 | 0.310 | 0.888 | W | |
| 1995/05/02 | 19:48 | 43.8 | 84.7 | 5.8 | 2.510 | 0.911 | W | #2 |
| 1995/05/07 | 15:16 | 20.3 | 109.4 | 5.1 | 0.062 | 0.938 | E | |
| 1995/07/10 | 04:31 | 22.0 | 99.2 | 6.2 | 173.323 | 0.921 | W | #5 |
| 1995/07/12 | 05:46 | 22.0 | 99.3 | 7.3 | 9.236 | 0.888 | W | #5> |
| 1995/07/22 | 06:44 | 36.5 | 103.0 | 5.8 | 0.257 | 0.977 | W | |
| 1995/09/20 | 11:14 | 35.0 | 118.0 | 5.2 | 0.369 | 0.907 | E | |
| 1995/10/06 | 06:26 | 39.8 | 118.5 | 5.0 | 285.194 | 0.505 | E | |
| 1995/10/24 | 06:46 | 25.9 | 102.2 | 6.5 | 1.491 | 0.876 | W | |
| 1995/12/18 | 12:56 | 34.6 | 97.3 | 6.2 | 0.211 | 0.570 | W | |
| 1995/12/20 | 18:07 | 34.6 | 97.5 | 5.5 | 0.211 | 0.591 | W | |
| 1996/02/03 | 17:14 | 27.2 | 100.3 | 7.0 | 3.648 | 0.707 | W | #11 |
| 1996/02/05 | 00:58 | 27.0 | 100.3 | 6.0 | 3.200 | 0.722 | W | #11 |
| 1996/02/06 | 15:36 | 27.1 | 100.4 | 5.6 | 2.983 | 0.704 | W | |
| 1996/03/19 | 23:00 | 39.9 | 76.8 | 6.9 | 1.362 | 0.866 | W | #1 |
| 1996/05/03 | 11:32 | 40.8 | 109.6 | 6.4 | 6.194 | 0.865 | E | |
| 1996/09/25 | 03:24 | 27.2 | 100.3 | 5.7 | 3.648 | 0.707 | W | |
| 1996/12/21 | 16:39 | 30.7 | 99.6 | 5.5 | 0.410 | 0.659 | W | |
| 1997/01/21 | 09:47 | 39.6 | 77.4 | 6.4 | 0.472 | 0.777 | W | |
| 1997/01/21 | 09:48 | 39.6 | 77.4 | 6.3 | 0.472 | 0.777 | W | |
| 1997/01/30 | 17:59 | 22.4 | 101.4 | 5.5 | 2.905 | 0.917 | W | #12 |
| 1997/03/01 | 14:04 | 39.5 | 76.9 | 6.0 | 0.448 | 0.834 | W | |
| 1997/04/06 | 07:46 | 39.5 | 76.8 | 6.3 | 0.719 | 0.824 | W | |
| 1997/04/06 | 12:36 | 39.6 | 76.9 | 6.4 | 2.142 | 0.847 | W | |
| 1997/04/11 | 13:34 | 39.7 | 76.8 | 6.6 | 0.701 | 0.842 | W | |
| 1997/04/13 | 05:09 | 39.5 | 76.9 | 5.5 | 0.448 | 0.834 | W | |
| 1997/04/16 | 02:19 | 39.6 | 76.9 | 6.3 | 2.142 | 0.847 | W | |
| 1997/05/31 | 14:51 | 25.6 | 117.0 | 5.2 | 1.206 | 0.843 | E | |

(Continued on Next Page...)

(Continuation of Table 2)

| Date | Time | Long. | Lat. | Mag. | $\lambda$ | $b_{M_L}$ | Reg. | Remark |
|---|---|---|---|---|---|---|---|---|
| 1997/07/28 | 02:31 | 33.7 | 122.2 | 5.1 | 0.976 | 0.852 | E | |
| 1997/10/18 | 01:35 | 39.6 | 77.0 | 5.5 | 1.886 | 0.809 | W | |
| 1998/01/10 | 11:50 | 41.1 | 114.3 | 6.2 | 0.169 | 0.760 | E | #9 |
| 1998/03/19 | 21:51 | 40.2 | 76.8 | 6.0 | 15.886 | 0.760 | W | #1 |
| 1998/05/29 | 05:11 | 37.8 | 79.2 | 6.2 | 0.584 | 0.836 | W | |
| 1998/05/30 | 05:28 | 37.8 | 79.2 | 5.5 | 0.584 | 0.836 | W | |
| 1998/07/28 | 12:51 | 41.8 | 81.6 | 5.5 | 17.667 | 0.889 | W | |
| 1998/08/02 | 12:40 | 39.6 | 77.5 | 6.0 | 7.790 | 0.710 | W | #1 |
| 1998/08/27 | 17:03 | 39.9 | 77.9 | 6.6 | 5.783 | 0.739 | W | #1> |
| 1998/11/20 | 19:38 | 27.3 | 100.9 | 6.2 | 6.700 | 0.678 | W | |
| 1999/01/29 | 13:44 | 44.7 | 115.7 | 5.2 | 0.063 | 0.781 | E | |
| 1999/01/30 | 11:51 | 41.5 | 88.9 | 5.6 | 1.146 | 0.795 | W | |
| 1999/03/11 | 21:18 | 41.2 | 114.6 | 5.6 | 2.256 | 0.737 | E | |
| 1999/03/15 | 18:42 | 41.8 | 82.7 | 5.6 | 2.800 | 0.814 | W | |
| 1999/04/08 | 21:10 | 43.4 | 130.3 | 7.0 | 0.106 | 0.675 | E | |
| 1999/11/01 | 21:25 | 39.8 | 113.9 | 5.6 | 1.072 | 0.756 | E | |
| 1999/11/29 | 12:10 | 40.4 | 123.2 | 5.4 | 0.546 | 0.650 | E | |
| 2000/01/12 | 07:43 | 40.5 | 123.1 | 5.1 | 18.084 | 0.644 | E | #2< |
| 2000/01/15 | 06:09 | 25.5 | 101.1 | 5.9 | 0.752 | 0.980 | W | |
| 2000/01/15 | 07:37 | 25.5 | 101.1 | 6.5 | 0.752 | 0.980 | W | |
| 2000/01/27 | 04:55 | 24.2 | 103.6 | 5.5 | 0.113 | 0.842 | W | |
| 2000/01/31 | 15:26 | 38.3 | 89.0 | 5.7 | 2.250 | 0.600 | W | |
| 2000/06/06 | 18:59 | 37.1 | 104.0 | 5.9 | 2.663 | 0.949 | W | #4 |
| 2000/09/12 | 08:27 | 35.3 | 99.3 | 6.6 | 1.175 | 0.705 | W | #9 |
| 2001/02/23 | 08:09 | 29.4 | 101.2 | 6.0 | 3.182 | 0.732 | W | |
| 2001/04/12 | 18:46 | 24.7 | 98.9 | 5.9 | 7.228 | 0.623 | W | #5 |
| 2001/05/24 | 05:10 | 27.6 | 100.9 | 5.8 | 8.796 | 0.667 | W | |
| 2001/10/27 | 13:35 | 26.2 | 100.6 | 6.0 | 1.598 | 0.787 | W | |
| 2001/11/19 | 05:59 | 35.9 | 94.0 | 5.7 | 0.509 | 0.539 | W | |
| 2001/11/20 | 01:45 | 35.8 | 93.8 | 5.6 | 0.435 | 0.514 | W | |
| 2002/06/29 | 01:19 | 43.5 | 130.6 | 7.2 | 0.235 | 0.693 | E | |
| 2002/09/15 | 16:39 | 44.7 | 130.3 | 5.6 | 0.046 | 0.702 | E | |
| 2002/12/14 | 21:27 | 39.8 | 97.3 | 5.9 | 0.734 | 0.885 | W | |

(Continued on Next Page...)

(Continuation of Table 2)

| Date | Time | Long. | Lat. | Mag. | $\lambda$ | $b_{M_L}$ | Reg. | Remark |
|---|---|---|---|---|---|---|---|---|
| 2002/12/25 | 20:57 | 39.6 | 75.4 | 5.7 | 7.084 | 0.697 | W | #6 |
| 2003/02/24 | 10:03 | 39.5 | 77.2 | 6.8 | 58.847 | 0.917 | W | |
| 2003/02/25 | 11:52 | 39.5 | 77.3 | 5.5 | 35.024 | 0.940 | W | #1< |
| 2003/03/12 | 12:47 | 39.5 | 77.4 | 5.9 | 10.727 | 0.950 | W | #1< |
| 2003/04/17 | 08:48 | 37.5 | 96.8 | 6.6 | 0.471 | 0.768 | W | |
| 2003/05/04 | 23:44 | 39.4 | 77.3 | 5.8 | 1.666 | 0.972 | W | #1< |
| 2003/07/21 | 23:16 | 26.0 | 101.2 | 6.2 | 0.785 | 0.816 | W | #3 |
| 2003/08/16 | 18:58 | 43.9 | 119.7 | 5.9 | 0.216 | 0.677 | E | |
| 2003/09/02 | 07:16 | 38.5 | 75.1 | 5.9 | 5.782 | 0.915 | W | #1< |
| 2003/10/16 | 20:28 | 26.0 | 101.3 | 6.1 | 0.668 | 0.778 | W | #3 |
| 2003/10/25 | 20:41 | 38.4 | 101.2 | 6.1 | 0.237 | 0.888 | W | |
| 2003/10/25 | 20:48 | 38.4 | 101.1 | 5.8 | 0.496 | 0.900 | W | |

Table 3: Calculation of complete gambling scores. See the explanation of Equation (17) for the meanings of $A_+$, $R_+$, $A_-$, $R_-$, and $R$.

| Year | $A_+$ | $R_+$ | $A_-$ | $R_-$ | $R$ |
|---|---|---|---|---|---|
| 1990 | 31.798 | 0 | 2367.152 | -8770.499 | -6435.145 |
| 1991 | 86.640 | 2.035 | 2312.310 | -284.651 | 1943.055 |
| 1992 | 46.301 | 0 | 2352.649 | -729.134 | 1577.213 |
| 1993 | 41.159 | 81.131 | 2357.791 | -387.456 | 2010.306 |
| 1994 | 30.837 | 8.012 | 2368.113 | -5386.171 | -3040.882 |
| 1995 | 45.818 | 42.488 | 2353.132 | -2885.375 | -535.573 |
| 1996 | 66.236 | 944.514 | 2332.714 | -115.125 | 3095.867 |
| 1997 | 51.433 | 17.081 | 2347.517 | -2299.918 | 13.247 |
| 1998 | 43.699 | 679.349 | 2355.251 | -415.408 | 2575.493 |
| 1999 | 31.021 | 0 | 2367.929 | -3222.886 | -885.977 |
| 2000 | 32.525 | 211.639 | 2366.425 | -1846.686 | 698.853 |
| 2001 | 29.776 | 4.258 | 2369.174 | -136.012 | 2207.645 |
| 2002 | 34.222 | 4.243 | 2364.728 | -2873.434 | -538.685 |
| 2003 | 33.789 | 474.525 | 2365.161 | -1782.491 | 1023.407 |
| sum | 605.253 | 2469.275 | 32980.048 | -31135.247 | 3708.824 |

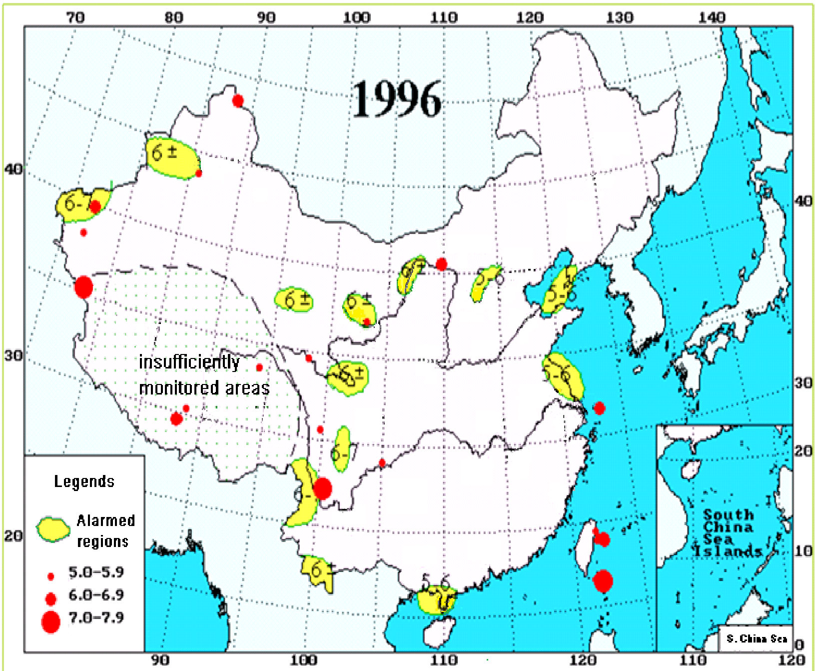



Figure 1: Chinese annual earthquake predictions in 1996. The alarmed regions are marked in yellow and the earthquakes with magnitudes of 5 and above are represented by red dots. The numbers on the alarmed regions are the magnitude ranges of the expected future earthquakes.

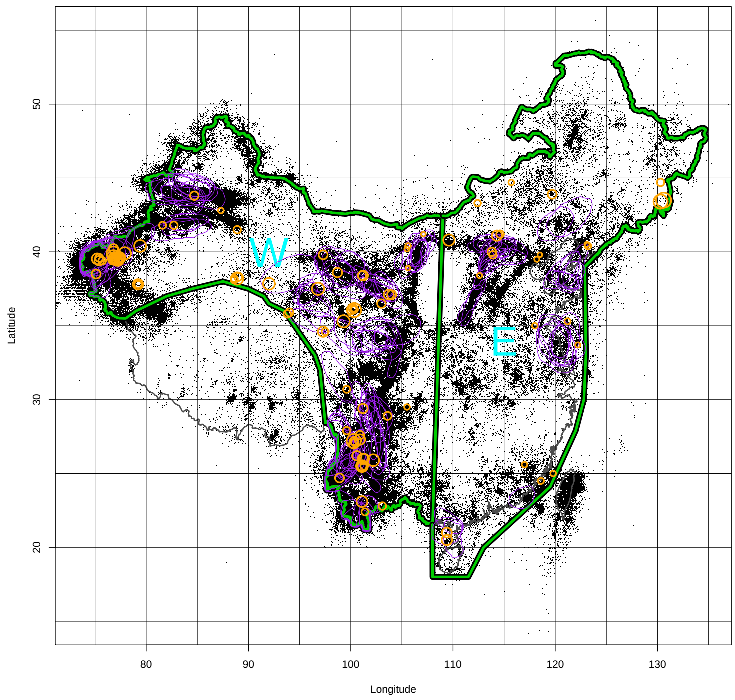



Figure 2: Division of the eastern and western parts, distribution of earthquake locations (black dots, $M_L \geqslant 3.5$) during 1970 – 2003 and distribution of CEA alarmed regions (purple closed curves) during 1990 – 2003. The orange circles represent the locations of the target earthquakes ($M_S \geqslant 5.0$ in the eastern part and $M_S \geqslant 5.5$ in the western part).

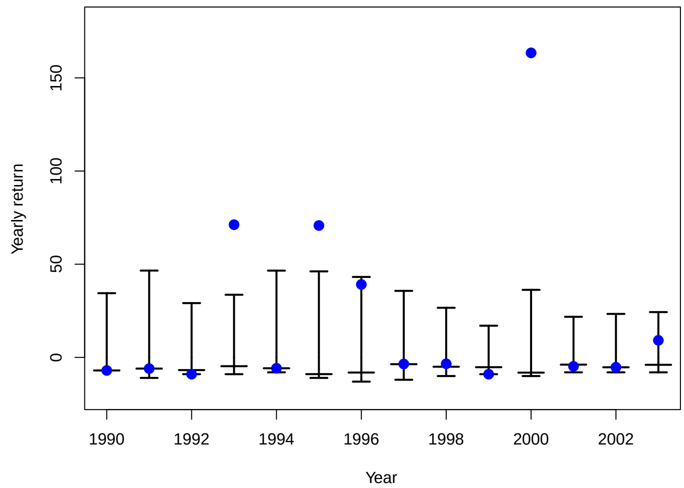



Figure 3: Yearly reputation return of CEA predictions. The bar plots show the 5% and 95% percentiles and the median of the return under the assumptions of the reference models.

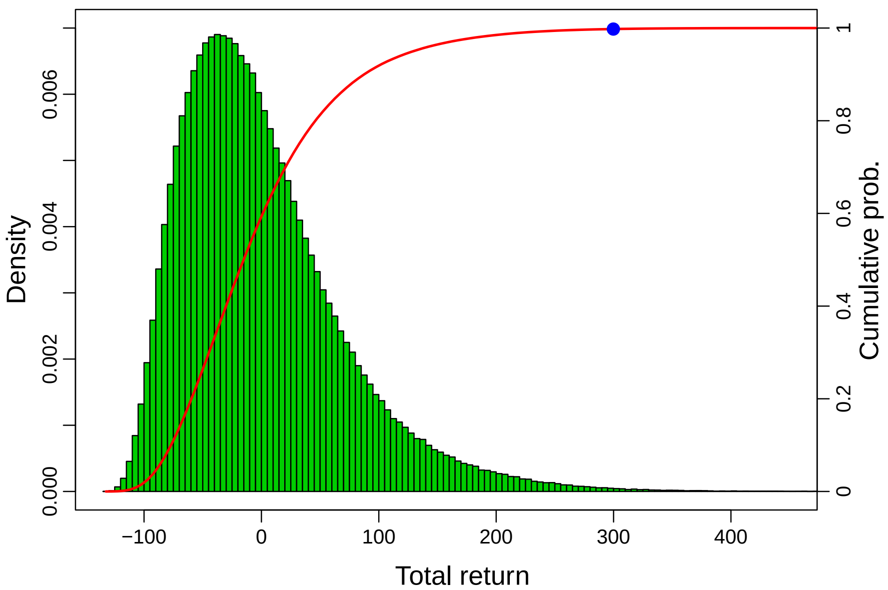
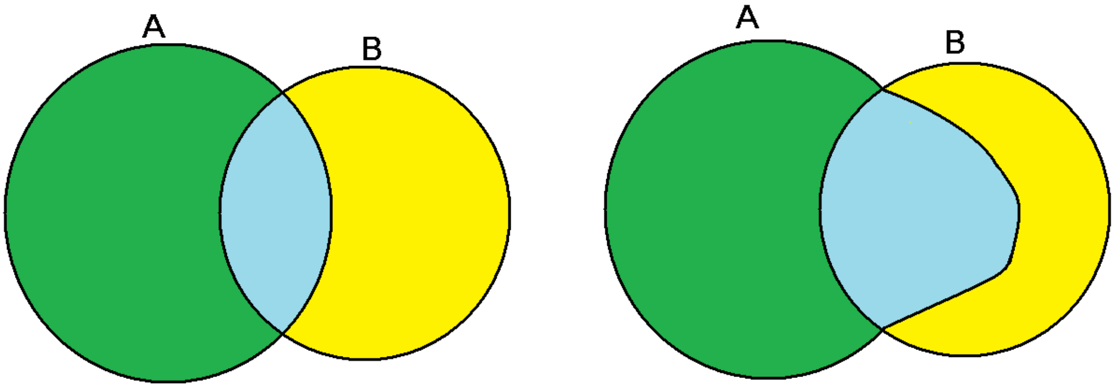



Figure 4: Random distributions of total return under the reference model (green histogram) and its cumulative probability function (red curve). The total score is marked by a blue dot on the cumulative probability curve.




(a) (b)

Figure 5: (a) An illustration of the relation between the R scores for the CEA annual predictions and the nonhomogeneous Poisson model. (b) An illustration of a method for improving CEA predictions from nonhomogeneous Poisson model in the R score. A and B represents, respectively, the R scores for the CEA predictions and the nonhomogeneous Poisson model.

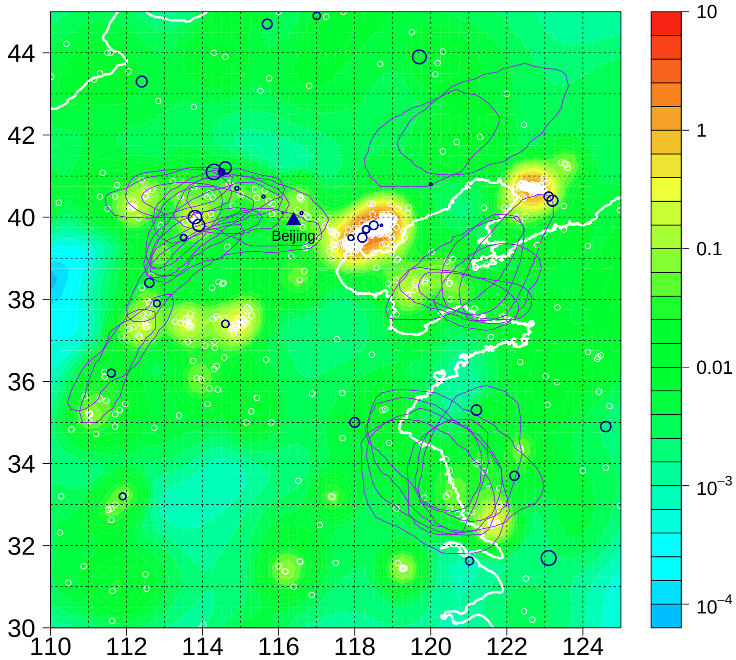



Figure 6: Seimicity rates of earthquakes ($M \geqslant 3.5$, unit: events/(year·deg$^2$) during the time period from the beginning 1970 to the end of 1989 in North China, obtained by smoothing seismicity of $M \geqslant 3.5$ events from 1970 to 1989 using variable kernel functions. Earthquakes of $M \geqslant 4.0$ before and after the end of 1989 were plotted in white and blue circles, respectively.