

## **2011 SCEC Report 11035**

### **FULL EARTH HIGH-RESOLUTION EARTHQUAKE FORECASTS**

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### **SUMMARY**

Since 1977 we have developed statistical short- and long-term earthquake forecasts to predict earthquake rate per unit area, time, and magnitude. The forecasts are based on smoothed maps of past seismicity and assume spatial and temporal clustering. Our new program forecasts earthquakes on a  $0.1^\circ$  grid for a global region 90N–90S latitude. We use the PDE catalog that reports many smaller quakes ( $M \geq 5.0$ ). For the long-term forecast we test two types of smoothing kernels based on the power-law and on the spherical Fisher distribution. We employ adaptive kernel smoothing which improves our forecast both in seismically quiet and active areas. Our forecasts can be tested within a relatively short time period since smaller events occur with greater frequency. The forecast efficiency can be measured by likelihood scores expressed as the average probability gains per earthquake compared to spatially or temporally uniform Poisson distribution. Another method uses the error diagram to display the forecasted point density and the point events. Our short-term forecasts also assume temporal clustering described by a variant of Omori's law. Like the long-term forecast, the short-term version is expressed as a rate density in location, magnitude, and time. Any forecast with a given lower magnitude threshold can be recalculated, using the tapered Gutenberg-Richter relation, to larger earthquakes with the maximum (corner) magnitude determined for appropriate tectonic zones.

# TECHNICAL REPORT

## 1 Introduction

We have developed a time-independent (long-term) and time-dependent (short-term) earthquake forecast by using several earthquake catalogs (Kagan & Knopoff, 1977; 1987; Kagan & Jackson, 1994; Jackson & Kagan, 1999). The importance of earthquake forecasting for seismic hazard and risk estimation and the difficulty of resolving basic differences in forecast models have motivated an international effort to report and test earthquake forecasts. That effort is organized by the Collaboratory for Study of Earthquake Predictability (CSEP) (Schorlemmer & Gerstenberger, 2007; Schorlemmer *et al.*, 2010; Marzocchi & Zechar, 2011).

Our purpose is to adapt a clustering model that we used to make testable forecasts over large regions of the western Pacific (Kagan & Jackson, 1994; Jackson & Kagan, 1999; Kagan & Jackson, 2000) to include long- and short-term regional and worldwide forecasts in areas designated as natural laboratories by CSEP. Our earlier effort (Kagan & Jackson, 2011) forecasts seismicity quasi-globally from 75N to 75S latitude with low-resolution  $0.5^\circ$  cells. To get the test running as quickly as possible, we adopted arbitrary parameter values, similar to those that Kagan & Jackson (2000) used. Later we calculated optimized forecast parameters (Kagan & Jackson, 2011, Fig. 11) which were implemented in our new high-resolution forecast described here.

## 2 Smoothing Kernel Selection

Our previous regional and global forecasts (Kagan & Jackson, 1994; Jackson & Kagan, 1999; Kagan & Jackson, 2000; 2011) have been based on fixed kernel smoothing. We selected a fixed kernel with the degree of spatial smoothing controlled by the function which is asymptotic to a power-law at distances much larger than  $r_s$

$$f(r) = \frac{1}{\pi} \times \frac{1}{r^2 + r_s^2}, \quad (1)$$

where  $r$  is epicenter distance,  $r_s$  is the scale parameter of about 7.5 km and  $r \leq 1000$  km (Kagan & Jackson, 2011).

Unfortunately, the 1000 km distance limit causes sharp discontinuities in the smoothed maps as can be seen in Figs. 1, 2 by Kagan & Jackson (2011) around the Hawaii islands. These discon-

tinuities can be avoided if we use a kernel with the whole Earth support. However, in this case the choice of available kernels is significantly restricted. If we employ a power-law kernel like (1), its normalization on a sphere involves the application of cumbersome hyper-geometric functions. Practically, the best simple expression for a spherical surface kernel is the Fisher distribution (Fisher, 1953, p. 296; Fisher *et al.*, 1987, Eqs. 4.19–4.23; Mardia & Jupp, 2000, Eq. 9.3.4).

These authors propose expressions for the spherical Fisher distribution in a general, complicated form. For our purpose we assume that the distribution center is at a pole of a sphere and the distribution has a rotational symmetry. Then the probability density function (PDF) of the spherical Fisher distribution is

$$\begin{aligned} f(\rho, \eta) &= \frac{\kappa}{4\pi \sinh \kappa} \exp(\kappa \cos \rho) \times \sin(\rho) \times \phi(\eta) \\ &= \frac{\kappa}{2\pi(e^\kappa - e^{-\kappa})} \exp(\kappa \cos \rho) \times \sin(\rho) \times \phi(\eta), \end{aligned} \quad (2)$$

where  $\eta$  is an azimuthal angle,  $\phi(\eta)$  is angular azimuthal distribution density,  $\rho = r/R$  is the epicenter distance in radians,  $R$  is the Earth radius, and  $\kappa$  is a scale parameter.

It is more convenient to consider the Fisher distribution as depending only on distance, i.e., we take  $\phi(\eta) = 1/(2\pi)$ . For the distance distribution only, since  $\sin(\rho) \delta \rho$  is the differential distance element on a sphere,  $\sin(\rho)$  term in (2) can be omitted as well as  $1/(2\pi)$  term. Then, the cumulative spherical Fisher distribution function is

$$F(\rho) = \frac{\exp[(\kappa(\cos \rho) - 1)] - 1}{e^{-2\kappa} - 1}. \quad (3)$$

For  $\kappa > 100$ , these equations can be simplified

$$f(\rho) \approx \kappa \exp[\kappa(\cos \rho - 1)] = \kappa \exp[-\kappa(\sin^2(\rho/2))]. \quad (4)$$

Since for small distance values ( $\sin \rho \approx \rho$ ), the above equation suggests that the probability density decays like a Gaussian function. In our California forecasts we applied the Gaussian as well as the power-law kernel smoothing distributions (Werner *et al.*, 2011) and found that they are similar in their results.

To carry out the adaptive smoothing based on the Fisher distribution, we follow the advice of Silverman (1986, Ch. 5.3): we first create an initial weight value estimate for earthquake epicenters location ( $\chi_i$ ) by using Eq. 4

$$\chi_i = \sum_{j=1}^N f(\rho_{ij}), \quad (5)$$

where  $N$  is the number of earthquakes and  $\rho_{ij}$  is the distance between two epicenters.

Then local bandwidth factors ( $\Lambda_i$ ) are defined

$$\Lambda_i(\rho) = \kappa (\chi_i/\chi_g)^\alpha, \quad (6)$$

where  $\chi_g$  is the geometric mean of  $\chi_i$

$$\log \chi_g = \frac{1}{N} \sum_{i=1}^N \log(\chi_i). \quad (7)$$

The  $\kappa$ -values in Eqs. 5 and 6 could be different, but as Silverman (1986, Ch. 5.3) suggests and we tested (see below), the parameter value in the initial estimate does not significantly influence the final result. The forecast density at any point  $\vec{r}$  is then estimated by

$$\mu(\vec{r}) = \sum_{i=1}^N \Lambda_i(\vec{r} - \vec{r}_i), \quad (8)$$

In Fig. 1 we display two kernel examples: the densities for the power-law and for the spherical Fisher distribution. The density maximum for the Fisher law can be calculated by equating derivative of its PDF (2) to zero. For large  $\kappa$  we obtain

$$\cos \rho - \kappa \sin^2 \rho \approx 0. \quad (9)$$

Since for large  $\kappa$   $(\cos \rho) \uparrow 1$ , the distance for the maximum is

$$\rho_m \approx \arcsin \sqrt{1/\kappa}, \quad (10)$$

### 3 Optimizing and Testing Forecasts

Using the forecasted rate values ( $\lambda_i$  for cell centers in which earthquakes occurred) we compute

$$I_1 = \frac{1}{n} \sum_{i=1}^n \log_2 \frac{\lambda_i}{\xi}, \quad (11)$$

where  $n$  is the earthquake number during a forecast period and  $\xi$  is a similar rate for the event occurrence according to the Poisson process with a uniform rate over a region (Kagan, 2009, Eq. 7).  $I_1$  measures the degree to which the earthquakes in the test period are concentrated in cells where the forecast rate is high. Fig. 2 demonstrates that the values of  $I_0$  and  $I_1$  may be significantly different unless the cell size is much smaller than the smoothing distance  $\rho$ .

Fig. 2 demonstrates how the fixed Fisher kernel was optimized using earthquake history for 1969-2005 to forecast earthquake occurrence in 2006-2010. The red curve displays the potential gain of a forecast (specificity) – the scores increase for the narrower kernels.

Fig. 3 shows the worldwide long-term forecast made using an adaptive Fisher distribution kernel. Comparing it with Figs. 1, 2 by Kagan & Jackson (2011) it is obvious that the width of seismicity peaks at subduction zones is reduced. This is due to narrower kernels at concentrations of earthquake epicenters. Seismicity contours for the low activity regions are smoother than in the previous plot, because the adaptive kernels are broader in these places.

Optimizing the three parameters  $\kappa$ ,  $\alpha$ , and  $\epsilon$  is computationally challenging, so we've taken some shortcuts. We used a low-resolution grid (0.5 by 0.5 degrees) to estimate  $\kappa$  and  $\alpha$ , and we made only a partial search for the maximum likelihood values of all parameters. The model used in Fig. 3 is based on that approximate optimization. We regard it as a respectable model worthy of comparison to others, but the values could probably be improved by further optimization.

## 4 Outreach Activity

Our work on earthquake forecasting and its testing has been extensively reported in scientific literature (see below the list of publications) as well as in many presentations at meetings and workshops. The 11 March 2011 Tohoku, Japan, magnitude 9.1 earthquake and the ensuing tsunami near the east coast of the island of Honshu caused nearly 20,000 deaths and more than 300 billion dollars in damage, resulting in the worst natural disaster ever recorded (Geller, 2011; Stein *et al.*, 2011). The major issue in the enormous damage was a great difference between the expected and the observed earthquake magnitudes. The maximum magnitude size for Tohoku area (around 7.7) was proposed in the official hazard map (Geller, 2011; Stein *et al.*, 2011; Simons *et al.*, 2011). The evaluation of maximum possible earthquake was discussed in several of our previous publications. We prepared a few manuscripts (now in review) which update and enhance our results, we again propose that magnitude 9.0-9.7 earthquake are to be expected in subduction zones. These new results were reported in a several scientific meetings.

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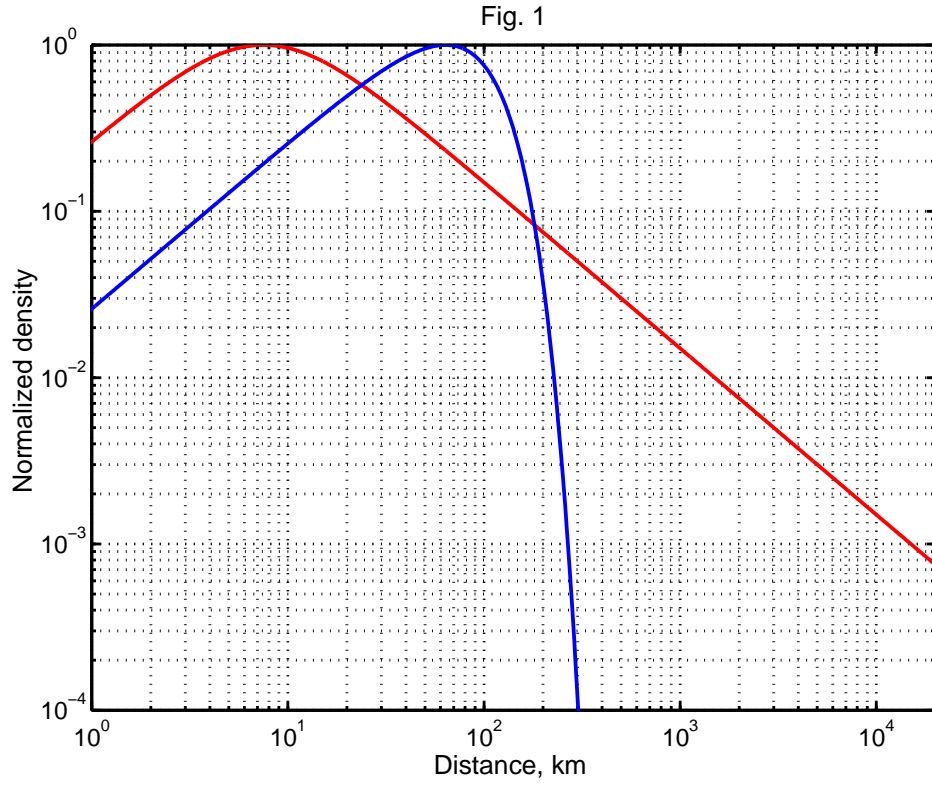


Figure 1:

Examples of kernel graphs: Red – power-law kernel with  $r_s = 7.5$  km; Blue – corresponds to the Fisher distribution kernels (Eq. 4) with  $\kappa = 10,000$ .

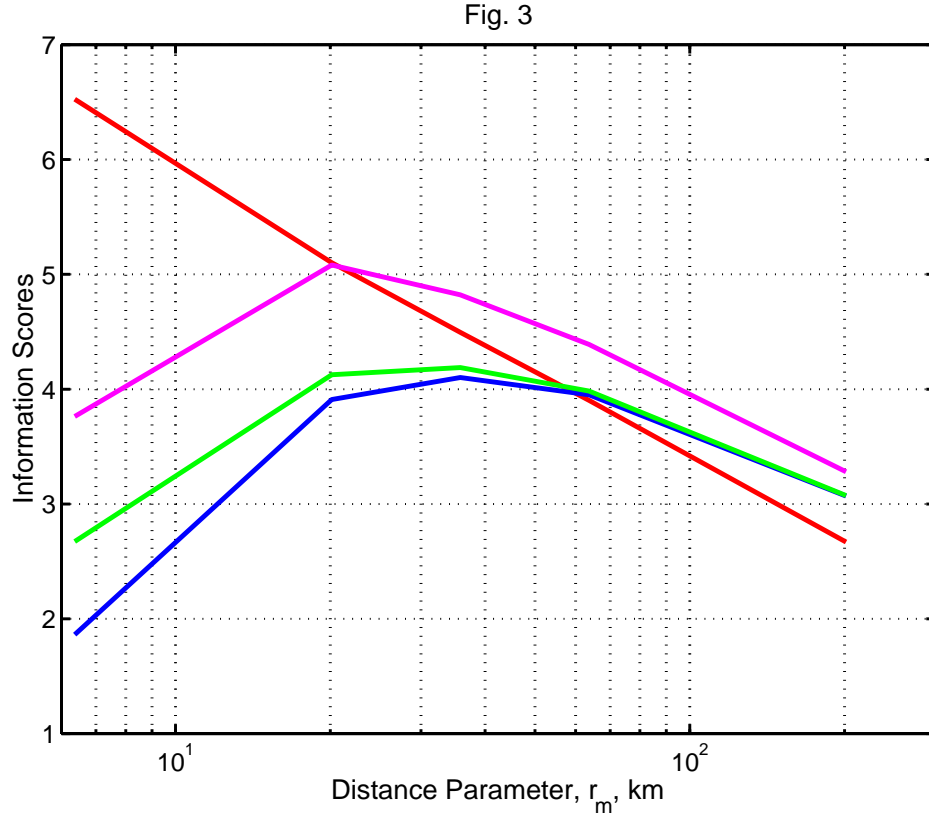


Figure 2:

Dependence of information scores on the smoothing scale parameter in the Fisher distribution  $r_m = R \times \rho_m(10)$  for the 2006-2010 forecast based on the PDE catalog for 1969-2005. The abscissa  $r_m$  values correspond to  $\kappa = 1,000,000; 100,000; 10,000 \times \sqrt{10}; 10,000; 1,000$  in this order. Red line is  $I_0$  score, blue –  $I_1$ , green –  $I_2$ , and magenta line is for  $I'_1$ .

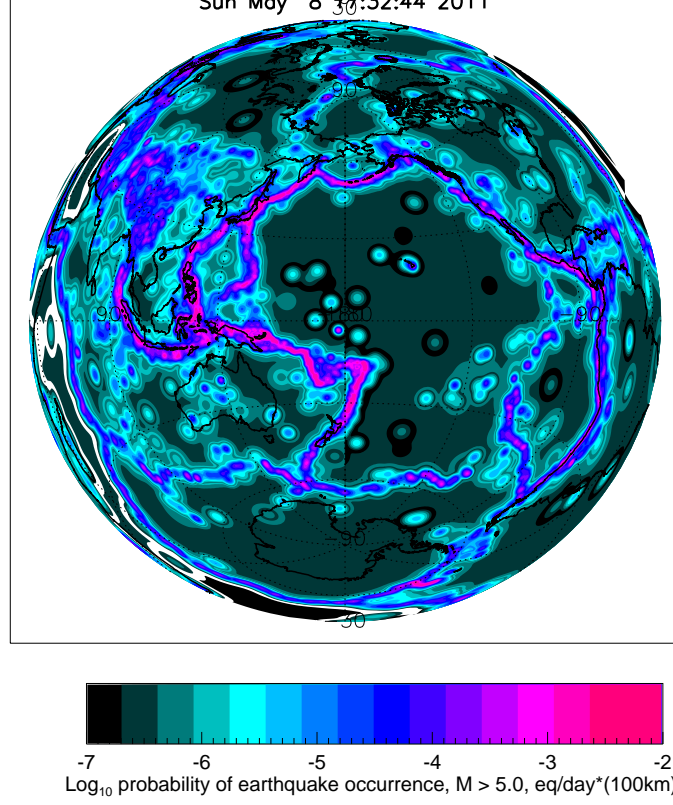


Figure 3:

Earthquake long-term rates based on smoothed seismicity from the PDE catalog 1969-2005. Adaptive smoothing kernel based on the Fisher spherical distribution (Eqs. 6–8) is used. Values of parameters are:  $\kappa = 100,000$ ,  $\alpha = 0.5$ , and  $\epsilon = 0.003$ . Earthquake occurrence is modelled by a time-independent Poisson process.

Below we list publications (with appropriate SCEC publication numbers) and abstracts, related to the topic of this proposal and finished during the proposal duration.

#### PUBLICATIONS SUPPORTED BY SCEC3:

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