

Is it possible to generate good Earthquake Risk Models using Genetic Algorithms?

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ABSTRACT

Understanding the mechanisms and patterns of earthquake occurrence is of crucial importance for assessing and mitigating the seismic risk. In this work we analyze the viability of using Evolutionary Computation (EC) as a means of generating models for the occurrence of earthquakes. Our proposal is made in the context of the "Collaboratory for the Study of Earthquake Predictability" (CSEP), an international effort to standardize the study and testing of earthquake forecasting models.

We use a standard Genetic Algorithm (GA) with real valued genome, where each allele corresponds to a bin in the forecast model. The design of an appropriate fitness function is the main challenge for this task, and we test three different proposals, all based on the log-likelihood of the candidate model against the training data set.

The resulting forecasting models are compared with statistical models traditionally employed by the CSEP community, using data from the Japan Meteorological Agency (JMA) earthquake catalog. Our results indicate promise for the use of GA as basis for constructing statistical earthquake forecast models. Based on these results, we identify research directions that we consider deserve more attention from the EC community.

Categories and Subject Descriptors

I.2.8 [Artificial Intelligence]: Problem Solving, Control Methods and Search Heuristic Methods; J.2 [Computer Application]: Physical Sciences and Engineering—*Earth and Atmospheric Sciences*

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General Terms

Real World Applications

Keywords

Earthquakes, Risk Models, Genetic Algorithms, Forecasting

1. INTRODUCTION

Earthquakes pose a huge risk for human society, in their potential for large scale loss of life and destruction of infrastructure. In the last decade, large earthquakes such as Sumatra (2004), Kashmir (2005), Sichuan (2008) and Tohoku (2011) caused terrible amounts of casualties.

Therefore, it is crucially important to understand the patterns and mechanisms behind the occurrence of earthquakes. This knowledge may allow us to create better seismic risk forecast models, indicating where, when and how often large earthquakes are expected to happen. Such information can be put to good use for mitigating damage through urban planning, civil engineering codes, emergency preparedness, et cetera.

Still, earthquake prediction is still a largely unsolved problem, and the specific geological mechanisms behind earthquake generation are not completely understood. Therefore this is a very active topic of research in the seismology community. There are many proposed models, drawing from both geophysical principles and statistical analysis of previous seismic activity.

Surprisingly enough, applications of Evolutionary Computation (EC) for this problem have been few and far between. Given that EC has some times managed to find better solutions than humans for many hard problems, we wonder if Artificial Evolution might not be able to find something that humans are missing.

Therefore, the goal of this paper is to explore the suitability of Evolutionary Computation to the problem of earthquake forecast generation. To this end, we outline the problem as understood today, with a focus on the "best practices" suggested by the *Collaboratory for the Study of Earthquake Predictability* (CSEP) for testing earthquake forecast models.

Using this information, we design and implement a simple Genetic Algorithm that evolves a forecast model, the

GAModel. We compare the GAModel with the Relative Intensity (RI) algorithm and an information-less forecast. These comparisons use the CSEP-recommended Area Skill Score (ASS) test, using data from the Japanese Meteorological Agency (JMA) between 2005 and 2012.

The GA-based forecasts are generally competitive when compared to the RI algorithm, even though they still have difficulty in some of the harder scenarios. The results show that while there is vast room for improvement, Evolutionary Algorithm approaches definitely have potential to collaborate with the study of Earthquake Predictability.

Section 2 of this paper outlines the earthquake prediction problem. Section 3 reviews how Evolutionary Computation has been used up until now in the context of seismic research. In section 4, we detail the Genetic Algorithm system for generating forecast models. In section 5 we compare the performance of this system with the RI algorithm, and the implications of the results are discussed in the last section.

2. THE EARTHQUAKE PREDICTION PROBLEM

In the field of seismology, there is a large number of model proposals for earthquake forecasting. These range from methods based on geophysical principles to purely statistical algorithms.

In this context, the Collaboratory Study for Earthquake Predictability (CSEP)¹ proposes a methodology for rigorous scientific testing of these widely varying models. The main form of this testing is through distributed virtual laboratories [6], to which multiple research groups submit their forecast methods. However, the CSEP also makes its testing suite publicly available, so that researchers can develop and test their models.

In many application domains, the lack of a unified testing protocol means that comparing methods developed by different research groups can be a great burden. The CSEP framework allows us to easily and objectively compare our proposed algorithms with other approaches.

The CSEP testing framework defines how to represent a forecast, and defines 6 statistical tests. These will be briefly outlined below.

2.1 Earthquake Forecast Model

The forecast target is defined as a geographical region, a starting date and an ending date. A forecast model will estimate the number (and sometimes the magnitude) of earthquakes happening within this target time/space.

A forecast is composed of *bins*. Each bin represents a geographical interval, measured in latitude and longitude, and sometimes a magnitude interval.

For example, in this paper we define the “kanto” region as the area covered by latitude N34.8 to N36.3, and longitude E138.8 to E140.3. This area is divided into 2025 (45x45) bins of approximately 5km^2 (Figure 1).

For each bin in the forecast we associate a (positive, integer) number of expected earthquakes for that bin. A good forecast is that which the number of estimated earthquakes in each bin corresponds to the actual number of earthquakes that occurs in the target time period.

2.2 Comparison Testing

¹<http://www.cseptesting.org>

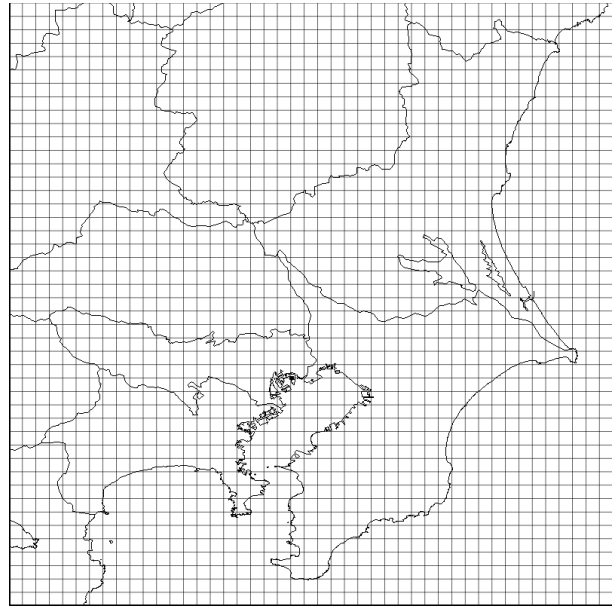


Figure 1: Target area for the Kanto region and its bins

The CSEP framework uses six different tests to compare earthquake forecasts. These are divided into two groups: log-likelihood based tests, and alarm based tests.

Log likelihood tests are based on a direct analysis of the similarity between the forecast and the actual earthquake catalog [10]. A Poissonian probability distribution function is used to measure the likelihood between the forecast and the data. Three statistical tests are defined using this metric: the *L-test*, which compares a forecast with the data, the *N-test*, which compares the total number of earthquakes forecast with the total number of observed earthquakes, and the *R-test*, which compares multiple forecasts at the same time. These tests require that all the forecasts being compared have the same number and size of bins.

Alarm based tests, on the other hand, are based on a threshold analysis [12]. All bins with forecast values above the threshold are added to an “alarm set”. The tests generate two values: a miss rate v , the proportion of earthquakes in the data that occurred in bins outside the alarm set; and the coverage rate τ , the proportion of the total bins in the model covered by the alarm set. Three alarm based tests are defined: the *Molcham Diagram* draws a path of v and τ based on varying values of the threshold, the *Area Skill Score (ASS)* summarizes a Molcham Diagram into a single number. A Receiver Operating Characteristic (ROC) can also be drawn using method of analysis. These tests do not take into account the total number of earthquakes, either from the forecast or the data.

2.3 The Relative Intensity Algorithm

The Relative Intensity (RI) algorithm is a commonly used benchmark for earthquake prediction models [5]. In this paper, we use it as goalpost to assess the suitability of evolutionary computation for this problem.

The working assumption behind the RI is that larger earth-

quakes are more likely to occur at locations of high seismicity in the past. Accordingly, the RI algorithm will estimate the number of earthquakes in a bin based on the number of earthquakes observed in the past for that bin, plus an attenuation factor that takes into account the seismicity of neighboring bins.

For more details on the implementation of the RI, please see the paper by Nanjo [5]. In the experiments in this paper, we use the following parameters: $b = 0.8$ and $s = 5$.

3. EVOLUTIONARY COMPUTATION FOR EARTHQUAKE RISK ANALYSIS

Reports of the application of Evolutionary Computation and related methods for the generation of earthquake forecasts are rather sparse. One such approach is described by Zhang and Wang [13]. They use Genetic Algorithms to fine tune an Artificial Neural Network (ANN), and use this system to produce a forecast. Unfortunately that paper did not provide enough information to reproduce the proposed GA+ANN system or their results. Zhou and Zu [14] also recently proposed a combination of ANN and EC, but their system only forecasts the magnitude parameter of earthquakes.

On the other hand, there are quite a few works using Evolutionary Computation methods for the estimation of parameter values in seismological models. These models are used to describe and understand particular characteristics of earthquakes or earthquake activity.

For example, there are many examples of using Evolutionary Computation to estimate the peak ground acceleration of seismically active areas [4, 1, 3]. Ramos [9] used Genetic Algorithms to decide the location of sensing stations in a seismically active area in Mexico. Nicknam et. al [7] and Kennett and Sambridge [2] used evolutionary computation to determine the Fault Model parameters (such as epicenter location, strike, dip, etc) of a given earthquake.

4. A FORECAST MODEL USING GENETIC ALGORITHMS

To investigate the ability of Evolutionary Computation to generate earthquake forecast models, we design and test a simple Genetic Algorithm. Let us call this system the *GAModel*.

An individual in *GAModel* will encode a forecast model as defined in the CSEP framework (see Section 2.1). The population will be trained on earthquake occurrence data for a fixed training period. The best generated individual will be compared with a model generated by the RI algorithm, and a skillless (random) model. This comparison is based on earthquake occurrence data for a test period immediately posterior to the training period.

By encoding the entire forecast model as one individual, we identified two main concerns while designing *GAModel*: First, as the forecast model contains a large number of bins, the genome of an individual will be respectively large. Evolutionary operators and parameters must be chosen carefully to guarantee convergence in a reasonable time, and avoid local optima.

Secondly, the design of the fitness function deserves a lot of attention, to avoid the risk of the system overfitting to the training data.

4.1 Genome Representation

In *GAModel*, each individual represents an entire forecast model. The genome is a real valued array X , where each element corresponds to one bin in the desired model (the number of bins n is defined by the problem). Each element $x_i \in X$ can take a value from $[0, 1)$. In the initial population, these values are sampled from a uniform distribution.

In the CSEP framework, a model is defined as a set of integer valued expectations, corresponding to the number of predicted earthquakes for each bin. To convert from the real valued chromosome to a integer forecast, we use a modification of the Poisson deviates extraction algorithm from [8] (Chapter 7.3.12).

Algorithm 1 Obtain a poisson deviate from a $[0, 1)$ value

```

Parameters  $0 \leq x < 1, \mu \geq 0$ 
 $L \leftarrow \exp(-\mu), k \leftarrow 0, prob \leftarrow 1$ 
repeat
  increment  $k$ 
   $prob \leftarrow prob * x$ 
until  $prob > L$ 
return  $k$ 

```

In Algorithm 1, x is the value taken from the chromosome, and μ is the average number of earthquakes observed across the entire training data. Note that in the original algorithm, $k - 1$ is returned. Because the log likelihood calculation used for model comparison discards forecasts that estimate 0 events in bins where earthquakes are observed, we modify the original algorithm here to make sure all bins estimate at least one event.

4.2 Fitness Function

The main challenge when applying an Evolutionary Computation method to any new application domain is usually the definition of an appropriate fitness function. Accordingly, the largest part of our effort in this work was to define a good fitness function for *GAModel*.

4.2.1 Simple Log Likelihood Fitness Function

Our first candidate was the log-likelihood between the forecast generated by an individual and the observed earthquakes in the training data, as described by Schorlemmer et. al. [10]. In simple terms, the log likelihood is a measure of how close a forecast is to a given data set.

Let $\Lambda = \{\lambda_1, \lambda_2, \dots, \lambda_n | \lambda_i \in \mathbb{N}\}$ be a forecast with n bins. In this definition, λ_i is the number of earthquakes that is forecast to happen in bin i . To derive Λ_X from an individual $X = \{x_1, x_2, \dots, x_n | 0 \leq x_i < 1\}$, we calculate each λ_i from x_i using Algorithm 1.

Let $\Omega = \{\omega_1, \omega_2, \dots, \omega_n | \omega_i \in \mathbb{N}\}$ be the observed earthquakes in the training data. The log likelihood between an individual's forecast Λ_X and the observed data Ω can be calculated as:

$$L(\Lambda_X | \Omega) = \sum_{i=0}^n -\lambda_i + \omega_i * \ln(\lambda_i) - \ln(\omega_i!) \quad (1)$$

There are two special cases that arise when any $\lambda_i = 0$. If $\lambda_i = 0$ and $\omega_i = 0$, then the value of the sum for that element is 1. If $\omega_i > 0$, then $L(\Lambda_X | \Omega) = -\infty$ and the forecast must be discarded. For more details on this, see [10].

In the Simple Log Likelihood fitness function, the value of $L(\Lambda_X|\Omega)$ is taken as the fitness value of the individual.

Early testing with the Simple Log Likelihood function showed that GAModel had a very strong tendency to overfit to the training data. This is natural, since there are differences between the seismicity of a larger period and a shorter one.

To avoid this overfitting, we have developed two alternative fitness functions.

4.2.2 Simulated Log Likelihood Fitness Function

In the Simulated Log Likelihood fitness function, we generate k “simulations” from the observed data Ω , and compare an individual’s forecast with all the simulated data.

Let $\hat{\Omega} = \{\hat{\omega}_1, \hat{\omega}_2, \dots, \hat{\omega}_k | \hat{\omega}_i \in \mathbb{N}\}$ be a simulated data set generated from Ω . Each $\hat{\omega}_i$ is taken randomly from a Poissonian distribution with mean ω_i .

To calculate the Simulate Log Likelihood fitness, we calculate the Log Likelihood of the forecast Λ_X generated by an individual X against each of the k simulated data sets ($L(\Lambda_X|\hat{\Omega}_1), \dots, L(\Lambda_X|\hat{\Omega}_k)$). We use the lowest of the k log likelihood values as the fitness of X .

The idea behind this fitness function is that by training against a number of similar, but slightly different training data sets at the same time, we might be able to avoid overfitting the forecast to the observed training data set.

4.2.3 Time-slice Log Likelihood Fitness Function

In the time-slice log likelihood fitness function we break up the training data set into smaller *slices*. These slices are based on the chronology of the earthquakes contained in the training catalog. The duration of each slice is the same as the duration of the test catalog.

Let’s consider an example where the target period for the forecast is one year, from 1/1/2014 to 1/1/2015, and the training data is taken from the 10 year period of 1/1/2004 to 1/1/2014. The time-slice log likelihood fitness function will divide the training data into ten 1-year periods, from 2004 to 2005, 2005 to 2006, and so on.

When an individual X is evaluated, we calculate the log likelihood of its forecast Λ_X against each of the time slices ($\Omega_{2004}, \Omega_{2005}, \dots, \Omega_{2013}$). The lowest value is used as the fitness of X .

The idea behind this fitness function is that the catalog data available for training will normally span a period of time much longer than the desired forecast. By breaking the training data into smaller periods, we are trying to make the evolutionary algorithm learn any time-repeating pattern that might exist in the data.

4.3 Evolutionary Operators and Parameters

GAModel uses a regular generational genetic algorithm. For selection, we use Elitism and Tournament selection.

We use a simple Uniform Crossover for the crossover operator. If a gene’s value falls outside the $[0, 1)$ boundary, it is truncated to these limits. For the mutation operator, we sample entirely new values from $[0, 1)$ for each mutated chromosome.

The parameters used for the evolutionary computation are described in Table 1. At this stage, we are not yet particularly worried with convergence speed of the system. Because of this, not a lot of effort was spent fine tuning these parameter’s values. Instead, these values were chosen by trial and

Population Size	500
Generation Number	100
Elite Size	1
Tournament Size	50
Crossover Chance	0.9
Mutation Chance (individual)	0.8
Mutation Chance (chromosome)	(genome size) ⁻¹

Table 1: Parameters for GAModel

error on a data region not used in the experiments of section 5.1, until an acceptable convergence time was found.

5. EXPERIMENTS

5.1 Experimental Data

The data used in these experiments comes from the Japan Meteorological Agency’s (JMA) catalog. The catalog lists earthquakes recorded by the sensing station network in Japan, along with the time, magnitude, latitude, longitude and depth of the hypocenter.

The part of the catalog used in this work spans a period from 2000 to 2013, and has over 220,000 earthquakes recorded in the Japanese archipelago. In order to better understand the predictive power of GAModel, we choose four areas from the catalog, which are used in the experiments below (see Figure 2). The first three areas focus on inland earthquakes, while the fourth area includes inland and off-shore events. We also only use earthquakes from the catalog with depth less than 100km.

1. **Kantou:** Kantou is the area at and nearby Tokyo. There is a large amount of seismic activity in the target period. In this study, we define this region as starting at N34.8, W138.8, with 2025 bins arranged in a 45x45 grid. Each bin corresponds to a 5kmx5km square.
2. **Kansai:** The Kansai area includes Kyoto, Osaka, Kobe and nearby cities. This area shows a relatively lower amount of seismic activity in the period considered. We define this region as starting at N34, W134.5, with 1600 bins arranged in a 40x40 grid. Each bin corresponds to a 5kmx5km square.
3. **Touhoku:** The Touhoku region is defined as the northern provinces of the main island. It shows some clusters of seismic activity during the period studied. We define this region as starting at N37.8, W139.8, with 800 bins arranged in a 40x20 grid. Each bin corresponds to a 10kmx10km square.
4. **East Japan:** This area corresponds to Japan’s north-eastern coast. It includes both inland and off-shore events, which makes it more difficult to forecast. It also includes the location of the M9 earthquake of 2011. We define this region as starting at N37, W140, with 1600 bins arranged in a 40x40 grid. Each bin corresponds to a 10kmx10km square.

5.2 Experimental Design

To test the ability of a Genetic Algorithm to generate an effective earthquake risk model, we perform a forecast experiment. In this experiment we compare three forecasts: a

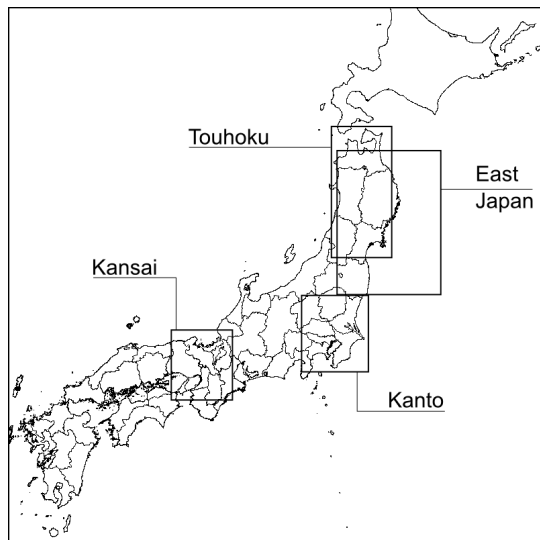


Figure 2: The four areas used in our experiments

randomly generated forecast, one generated by the RI algorithm, and a group of forecasts generated by the proposed method.

We define a “scenario” as a region and a forecast period. In this experiment, we will test 5 regions (all japan, pacific, kanto, tohoku, kansai), and 7 one-year periods (from 2005 to 2012), for a total of 40 scenarios.

Each scenario has a corresponding training window, which consists of the 5 years prior to the scenario’s forecast time. This training period is used by the RI algorithm and by the proposed method to generate their respective forecasts. For the sake of statistical testing, we generate 20 forecasts using the GAModel. Unless noted otherwise, all results reported are an average of these runs.

We compare the forecasts in three different ways: Using the log-likelihood between the forecast and the testing data, Using the ASS value, and visually by comparing the forecast maps of some significant scenarios.

5.3 Results and Comparison of forecast models

The results of our simulation experiments are summarized in Table 2. In this table we compare three forecast models: *random* is a randomly generated model, representing a total lack of information. *RI* is the forecast model generated by the Relative Intensity algorithm. This algorithm is deterministic, and always generates the same output for the same input data, so no variance is reported. *GA* is the GAModel system described in Section 4, using a time-slice fitness function. The reported results for the GAModel are the average of 20 runs, with the standard deviation reported in brackets.

6. CONCLUSION

- We choose the parameters hapzardly - a more careful parameter selection might improve the result (or at least the running time)

- There is a large number of problems related to the development of forecast models: Parameter optimization, model construction, earthquake clustering, etc.

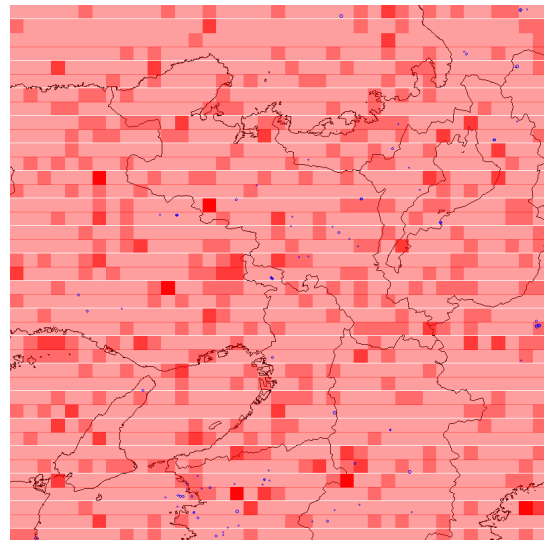


Figure 3: A random forecast (Kansai Region, 2007)

- On the evolutionary side, we think GA or ANNs might be a good idea.
- We encourage people to work on this with us.

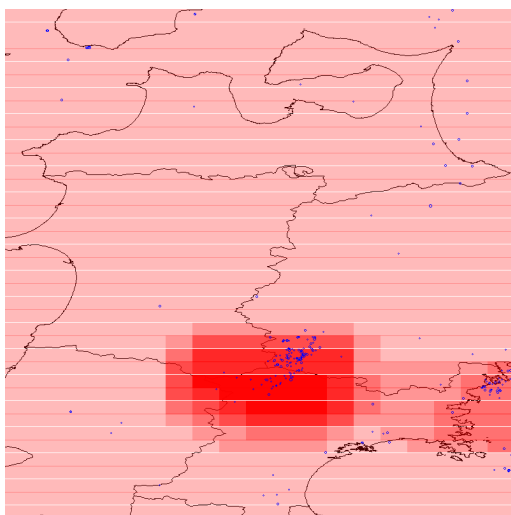
6.1 Future Work

Acknowledgements

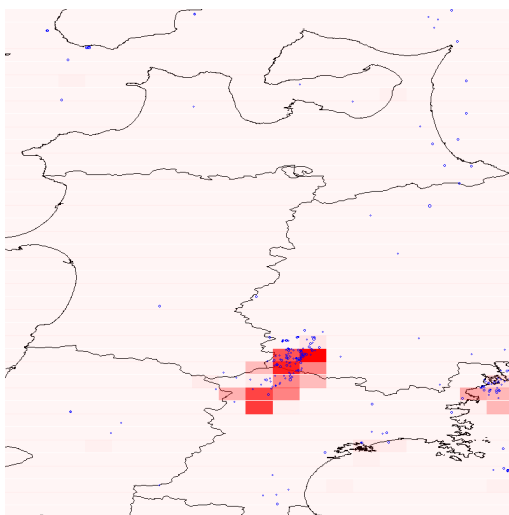
TODO: Check with Bogdan if we need to provide Acknowledgements for the JMA data.

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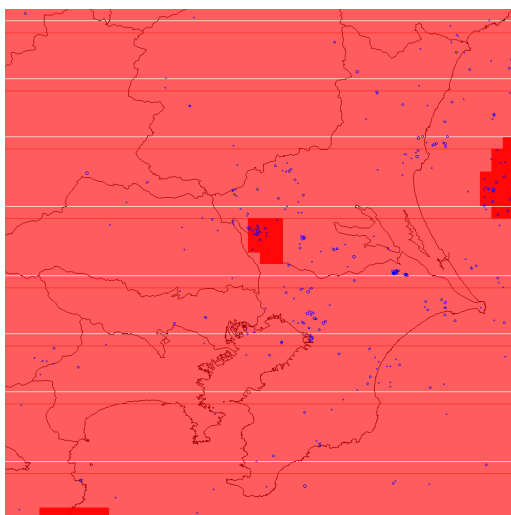
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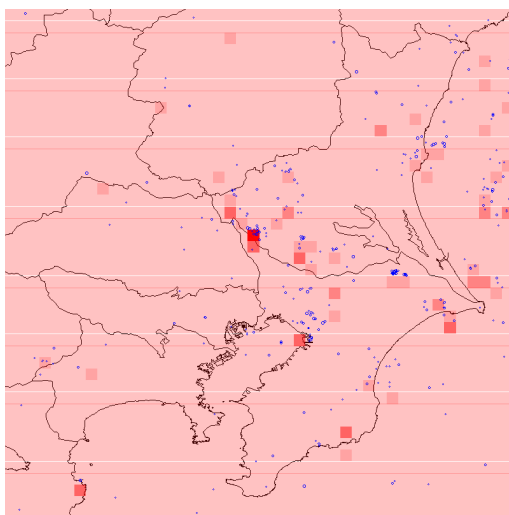
(a) Tohoku 2009, RI forecast



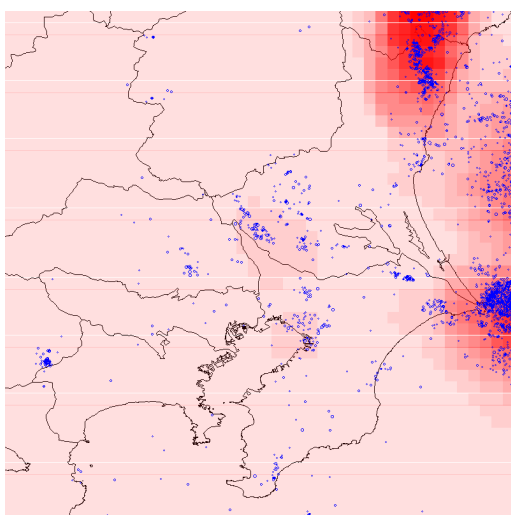
(b) Tohoku 2009, GA forecast



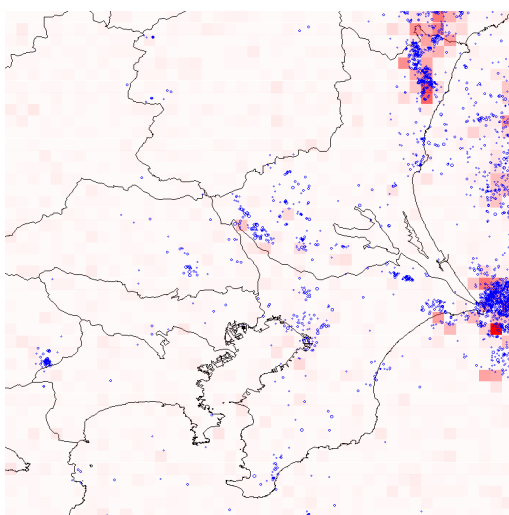
(c) Kanto 2010, RI forecast



(d) Kanto 2010, GA forecast



(e) Kanto 2012, RI forecast



(f) Kanto 2012, GA forecast

Figure 4: Some forecast images for the RI algorithm and the GAModel. Red squares indicate the intensity of the forecast. Blue circles indicate actual earthquakes in the test data. Note that the intensity of the red color indicates relative values in the forecast. In other words, uniform forecasts will tend to appear as a darker red color than forecasts with high and low values.

Scenario		Log Likelihood				Area Skill Score			
		Random	RI	GA	p-value	Random	RI	GA	p-value
East Japan	2005	-2666.11	-1049.82	-868.87 (20)	0.001 >	0.47	0.35	0.30 (0.02)	1
	2006	-6596.76	-2130.69	-2303.78 (98)	1	0.46	0.42	0.35 (0.01)	1
	2007	-6714.36	-1997.78	-2065.4 (85)	0.99	0.43	0.51	0.34 (0.02)	1
	2008	-8784.64	-6087.88	-6097.63 (264)	0.56	0.46	0.23	0.20 (0.03)	1
	2009	-6435.07	-2052.35	-1964.72 (106)	0.001 >	0.47	0.49	0.48 (0.02)	0.99
	2010	-6560.97	-2572.97	-2541.33 (121)	0.12	0.46	0.41	0.31 (0.01)	1
	2011	-31447.79	-47704.35	-51485.77 (536)	1	0.44	0.40	0.18 (0.01)	1
	2012	-19068.86	-5177.55	-6657.52 (478)	1	0.50	0.77	0.71 (0.01)	1
Kanto	2005	-3716.86	-2263.4	-2253.2 (16.5)	0.006	0.38	0.24	0.24 (0.04)	0.78
	2006	-3884.85	-2252.28	-2234.72 (14)	0.001 >	0.36	0.10	0.18 (0.01)	0.001 >
	2007	-3838.9	-2113.84	-2108.95 (11.1)	0.03	0.36	0.15	0.19 (0.02)	0.001 >
	2008	-3914.54	-2110.79	-2096.75 (11.8)	0.001 >	0.39	0.16	0.22 (0.3)	0.001 >
	2009	-4211.28	-2487.88	-2482.88 (10.3)	0.02	0.36	0.09	0.14 (0.01)	0.001 >
	2010	-4010.47	-2132.11	-2099.13 (16.3)	0.001 >	0.39	0.14	0.28 (0.03)	0.001 >
	2011	-17657.43	-20083.09	-19983.73 (144.4)	0.003	0.35	0.07	0.08 (0.02)	0.14
	2012	-10863.99	-3225.39	-4435.34 (248)	1	0.48	0.80	0.77 (0.01)	1
Kansai	2005	-2219.06	-1605	-1631.96 (26)	0.99	0.24	0	0.07 (0.02)	0.001 >
	2006	-2172.29	-1606	-1631.19 (23.9)	0.99	0.23	0	0.05 (0.01)	0.001 >
	2007	-2024.77	-1615	-1617.01 (2.3)	0.99	0.22	0	0.03 (0.01)	0.001 >
	2008	-2038.16	-1608	-1610.41 (1.54)	1	0.22	0	0.01 (0.01)	0.003
	2009	-2054.23	-1618	-1619.51 (2.58)	0.99	0.21	0	0.02 (0.01)	0.001 >
	2010	-2054.63	-1613	-1611.00 (2.27)	0.001 >	0.27	0	0.07 (0.02)	0.001 >
	2011	-2059.89	-1625	-1625.12 (2.46)	0.58	0.26	0	0.05 (0.03)	0.001 >
	2012	-2080.35	-1601	-1603.59 (2.92)	0.99	0.22	0	0.04 (0.02)	0.001 >
Tohoku	2005	-2552.61	-1067.38	-984.23 (84)	0.001 >	0.58	0.58	0.62 (0.01)	0.001 >
	2006	-2613.1	-1044.72	-1073.03 (154)	0.78	0.52	0.50	0.42 (0.03)	1
	2007	-2666.11	-1049.82	-999.64 (83.6)	0.007	0.51	0.51	0.41 (0.01)	1
	2008	-5124.54	-5007.49	-4704.15 (131)	0.001 >	0.36	0.05	0.18	0.001 >
	2009	-2737.47	-1049.22	-936.63 (60)	0.001 >	0.54	0.67	0.70 (0.01)	0.001 >
	2010	-2714.68	-1045.03	-1077.95 (136)	0.85	0.53	0.66	0.57	1
	2011	-3435.67	-2753.95	-2963.31 (88)	1	0.40	0.21	0.10 (0.01)	1
	2012	-3623.22	-1326.52	-1186.1 (45.3)	0.001 >	0.47	0.62	0.70 (0.05)	0.001 >

Table 2: Results from the simulation experiments. The parenthesis after the GA values are the standard deviation (average of 20 runs). The two “p-value” columns report the significance of the mean-test for the alternate hypothesis: “The GA average is higher than the RI result”.

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