International Symposium on Statistical Modeling and Real-time Probability Forecasting for Earthquakes

On the Occasion of Celebrating

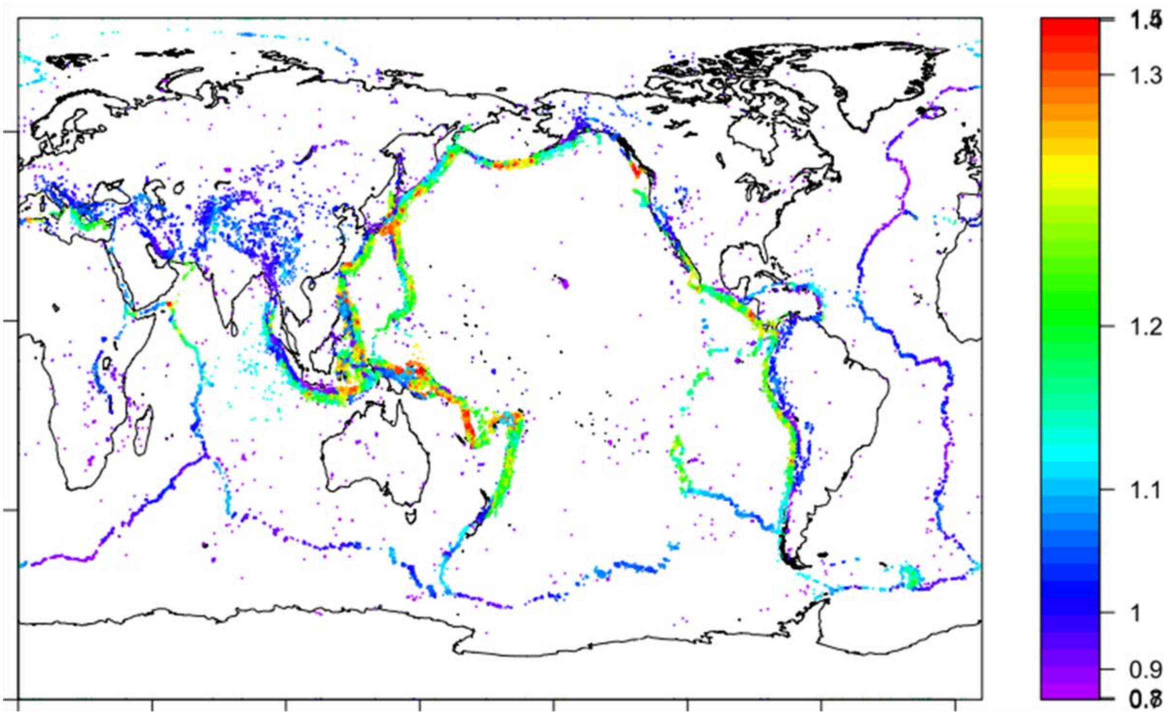
Prof. Yosi Ogata's

40-year Research Career in Statistical Seismology

統計数理研究所
The Institute of Statistical Mathematics

11/March/2012 to 14/March/2012

Global *p*-values of aftershock decay rate



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Programs

3/11 Sunday

Arrival

3/12 Monday

10:00-10:10 Opening: T. Higuchi (Director-general of ISM)

Session 1 (Chair: Max Werner, Jeremy Zechar and Ken'ichiro Yamashina)

Session 2 (Chair: Rodolfo Console and Mark Bebbington)

15:40-16:00 Coffee break

Session 3 (Chair: Warner Marzocchi and David Marsan)

18:30 Conference dinner

3/13 Tuesday

14:25-14:50 S. Nomura

Space-time models of repeating earthquakes in Parkfield segment

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14:50-15:15 N. Uchida

Repeating earthquake activity before and after the 2011 Tohoku earthquake

25

15:15-15:40 M. Okada

A Bayesian model, negative binomial model, for forecasting major aftershocks

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15:40-16:00 Coffee break

Session 3 (Chair: Bogdan Enescu and Zhongliang Wu)

16:00-16:25 C. Jiang

PI forecast with or without de-clustering: an experiment for the Sichuan-Yunnan region

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16:25-16:50 T. Iwata

Daily variation of the detection capability of earthquake and its influence on the completeness magnitude

28

16:50-17:15 J. Zhuang

On the criticality of branching models for earthquake occurrences

29

17:15-17:40 W. Marzocchi

On the frequency-magnitude distribution of converging boundaries

30

17:40-18:05 H. Tsuruoka

Development of tool for SEISmicity analysis: TSEIS and future scope

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3/14 Wednesday

Session 1 (Chair: Jiancang Zhuang and Takaki Iwata)

9:30-10:00 N. Hirata

Japanese national research program for earthquake prediction and the earthquake forecast testing experiment with statistical seismology

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10:00-10:30 M. Mutsu'ura

Systematic errors in the inversion analysis of GPS array data to estimate

Renewal models of seismic recurrence applied to paleoseismological and historical observations

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Because paleoseismology can extend the record of earthquakes back in time up to several millennia, it represents a great opportunity to study how earthquakes recur through time and thus to provide innovative contributions to seismic hazard assessment. A worldwide compilation of a database of recurrence from paleoseismology was developed in the frame of the ILP project "Earthquake Recurrence Through Time". From this database, integrated with historical information, we were able to extract 19 sequences with 5 up to 14 dated events on a single fault. By using the age of the paleoearthquakes and the historical earthquakes, with their associated uncertainty, we tested the null hypothesis that the observed inter-event times come from a uniform random distribution (Poisson model). We used the concept of likelihood for a specific sequence of observed events under a given occurrence model. The difference *dlnL* of the likelihoods estimated under two hypotheses gives an indication of which between the two hypotheses fits better the observations. To take into account the uncertainties associated with paleoseismological data, we used a Monte Carlo procedure. We computed the average and the standard deviation of *dlnL* for 1000 inter-event sets by choosing the occurrence time of each event within the limits of uncertainty provided by the observations. Still applying a Monte Carlo procedure, we estimated the probability that a value equal to or larger than a observed *dlnL* comes by chance from a Poisson distribution of inter-event times. These tests were carried out for a set of the most popular statistical models applied in seismic hazard assessment, i.e. the Log-normal, Gamma, Weibull, Double-exponential and Brownian Passage Time (BPT) distributions. In the particular case of the BPT distribution, we also show that the limited number of dated events determines a trend to reducing both the observed mean recurrence time and the coefficient of variation for the studied sequence which can possibly bias the results. Our results show that a renewal model, associated with a time dependent hazard, and some kind of predictability of the next large earthquake on a fault is significantly better than a plain time-independent Poisson model only for four, out of the 19 sites examined in this study,. The complete lack of regularity in the earthquake occurrence for more than 30% of the examined faults can be explained either by the large uncertainties in the estimate of paleoseismological occurrence times or by physical interaction between neighbouring faults.

A New Multi-dimensional Stress Release Statistical Model Based on Co-seismic Stress Transfer

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Following the stress release model proposed by Vere-Jones (1978), we developed a new multi-dimensional stress release model, which is a space-time-magnitude version based on multi-dimensional point processes. First, we interpreted the exponential hazard functional of the stress release model as the mathematical expression of static fatigue failure caused by stress corrosion. Then, we reconstructed the stress release model in multi-dimensions through incorporating four independent sub-models: the magnitude distribution function, the space weighting function, the loading rate function, and the co-seismic stress transfer model. Finally, we applied the new model to analyze the historical earthquake catalogues in North China. An expanded catalogue, which contains the information of origin time, epicenter, magnitude, strike, dip angle, rupture length, rupture width and average dislocation, is composed for the new model. The estimated model can simulate the variations of seismicity with space, time and magnitude. Compared with the previous stress release models with the same data, the new model yields much smaller values of AIC and AICc. The estimated model shows that 21 epicenters out of 37 are indicated as higher rates of earthquakes than the mean spatial seismic rate just before the related earthquakes. The map of predicted earthquake rates at the ending time (Jan. 1, 1997) suggests that the next destruct earthquake in North China is likely to occur in the regions south of Datong, north of Beijing and east of Hejian.

A Hidden Markov Model for the Earthquake Cycle

Mark Bebbington *Massey University*
Ting Wang *University of Otago*
David Harte *Statistics Research Associates*

Probabilistic earthquake forecasting tends to focus, in order, on aftershocks, triggered events and mainshocks, reflecting both the amount of relevant data available, and the degree of knowledge concerning the generating mechanisms.

The concept of a seismic cycle, including mainshocks, aftershocks, quiescence and foreshocks is an old one, dating back at least to Mogi (1968). However, there have been few attempts to statistically identify, or exploit, this for earthquake forecasting. Zhuang (2000) used change point analysis to identify an earthquake cycle off Cape Palliser in New Zealand from 1978 to 1996, dividing the seismicity into four periods: background seismicity, a relatively quiescent period, main shock and aftershock sequence, and a postseismic period. Pievatolo and Rotondi (2008) decomposed the observed seismicity from the Kresna region of Bulgaria into different phases according to variations in occurrence rate and probability distribution of inter-event time, finding two seismic cycles over 105 years with similar patterns of background activity—foreshocks, main shock, and aftershocks. However, there is no model for transitions between phases, and hence the change point methodology is not easily adapted for forecasting.

Bebbington et al. (2010) examined a cyclical model for the San Francisco Bay region. Notably the state variable was the accumulation of tectonic strain, not directly reflected in the observed data. Hidden Markov models (HMMs) form a remarkably general statistical framework for modelling partially observed systems, by assuming that the unobserved (or hidden) process is a Markov chain, and the observations are conditionally independent given the hidden states. The challenge is the interpretation of the resulting hidden state process. An intuitively attractive formulation is to see if the seismic cycle can be considered as a sequence of hidden states. This has been tried previously for earthquakes using a Markov modulated Poisson process (e.g., Ebel et al., 2007; Orfanogiannaki et al., 2010).

However, earthquakes are not usually independent, instead occurring in a self-exciting manner, i.e., previous events often trigger new ones. Thus there is not the conditional independence between events which is usual in HMMs. Hence we propose a new model—the Markov-modulated Hawkes process with stepwise decay (MMHPSD)—to investigate the variation in seismicity rate during a series of earthquake sequences including multiple mainshocks. The MMHPSD is a self-exciting process which switches among different states, in each of which the process has distinguishable background seismicity and decay rates. A variant on the EM algorithm is constructed to fit the model to data possessing immigration-birth features. This is applied to the Landers earthquake sequence, demonstrating that it is capable of capturing changes in the temporal seismicity patterns and the behaviour of main shocks, major aftershocks, secondary aftershocks and periods of quiescence. Future extension will be briefly discussed.

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Testing the forecast of aftershocks: a simple method with an example of application

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Test of aftershock forecast is intrinsically different from the 'standard' test for the forecast of mainshocks. Taking the 2008 Wenchuan aftershock sequence and the load-unload response ratio (LURR) forecast of aftershocks as an example, we discuss a simple test scheme which shares the similar statistical consideration to test the forecast of manshocks. In the test, the Ogata-transformed-time is used to make the transformed aftershock sequence homogenously random. While a test was conducted using the Molchan error diagram, other testing schemes are also valid to the transformed aftershock sequence.

A Bayesian approach to estimating the long-term probability of an M8 earthquake in Kanto, central Japan

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We attempt to estimate the long-term probability of an M8 earthquake in Kanto, central Japan. The Brownian passage time (BPT) model is applied to sets of historical earthquakes proposed by Ishibashi, Shishikura, and Shimazaki et al. An optimal model is obtained by the maximum likelihood method for each of the sets. The optimal parameters are not well constrained since each set includes a small number of earthquakes: five (Ishibashi), four (Shishikura), and three events (Shimazaki et al.). To obtain reliable probabilities, two weighting methods are introduced. First, we apply the weighted log-likelihood method, where the model parameters are estimated from the log-likelihood function, summed up with each log-likelihood weighted in proportion to the reliability of the data set. Second, the Akaike weight method is applied, where probabilities are estimated as the weighted average of every alternative model. The Akaike weight of each model represents the normalized relative likelihood of the model. The probabilities of the weighted log-likelihood function are within the ranges of those obtained for each set. In averaging the proposed sequence and using the Akaike weight, the probability of an M8 earthquake occurring in the next 30 years is estimated to be 2 to 4.6%, depending on the cutoff value of the Akaike weight.

Earthquake Forecasts from Inter-event Times Statistics

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Abstract. This study uses a statistic of earthquake inter-event times, called moment's ratio (MR), as a precursory alarm function for large earthquakes. MR is defined by the ratio of the first to second order moment (mean/variance) of earthquake inter-event times. This ratio has been shown to provide a rough estimation of the proportion of background events in the whole catalog (background fraction). The use of MR is motivated by its ability to characterize long term changes in the background seismicity which may show precursor to the occurrence of large events, so that we suppose it can be used in forecasting. To test the forecasting performance of MR, we prepared a composite catalog covering all Japan within the period 679-2011, which consists of the Japan Meteorological Agency (JMA) catalog for the period 1923-2011 and the Utsu historical seismicity records for the period 679-1922. This study uses a set of time periods which are chosen depending on the estimated magnitude of completeness; Then, MR values are estimated by sampling inter-event times with the earthquake random sampling (ERS) algorithm developed in my former work. ERS enhances inter-event times by simulation which is not possible when using the standard grid sampling. In a retrospective test of $M \geq 7$ target earthquakes, MR is spatially mapped for different learning time periods before the occurrence of target earthquakes. The start of the learning period is defined for each target earthquake depending on the catalog completeness whereas it ends a short time before the occurrence of the target event. The forecasting performance of MR is discussed using Molchan error and area skill score diagrams. The preliminary results show good performance when using the relative intensity (RI) forecasting method as a reference model.

Keywords Earthquake forecasting · Inter-event times · Alarm function · Molchan error diagrams

Widespread seismicity excitation and seismic shadow following the 2011 M=9.0 Tohoku, Japan, earthquake and its implications for seismic hazard

Shinji Toda (Disaster Prevention Research Institute, Kyoto University)

The 11 March 2011 Tohoku-chiho Taiheiyo-oki earthquake (Tohoku-oki earthquake) was followed by massive offshore aftershocks including 6 M≥7 and ~100 M≥6 shocks during the 9 months (until the end of 2011). It is also unprecedented that a broad increase in seismicity was observed over inland Japan at distances of up to 425 km from the locus of high seismic slip on the megathrust. Such an increase was not seen for the 2004 M=9.1 Sumatra or 2010 M=8.8 Chile earthquakes, but they lacked the seismic networks necessary to detect such small events. Here we explore the possibility that the rate changes are the product of static Coulomb stress transfer to small faults. We use the nodal planes of M≥3.5 earthquakes as proxies for such small active faults, and find that of fifteen regions averaging ~80 by 80 km in size, 11 show a positive association between calculated stress changes and the observed seismicity rate change, 3 show a negative correlation, and for one the changes are too small to assess. This work demonstrates that seismicity can turn on in the nominal stress shadow of a mainshock as long as small geometrically diverse active faults exist there, which is likely quite common in areas having complex geologic background like Tohoku. In Central Japan, however, there are several regions where the usual tectonic stress has been enhanced by the Tohoku earthquake, and the moderate and large faults have been brought closer to failure, producing M~5 to 6 shocks, including Nagano, near Mt. Fuji, Tokyo metropolitan area and its offshore. We confirmed that at least 5 of the seven large, exotic, or remote aftershocks were brought ≥0.3 bars closer to failure. Validated by such correlations, we evaluate the effects of the Tohoku event on the other subduction zones nearby and major active faults inland. The majorities of thrust faults inland Tohoku are brought farther from failure by the M9 event. However, we found that the large sections of the Japan trench megathrust, the outer trench slope normal faults, the Kanto fragment beneath Tokyo, the Itoigawa-Shizuoka Tectonic Line, and several other major faults were brought significantly closer to failure. Elevated seismicity in these areas is evident and sustained higher than normal during the 9 months after the Tohoku earthquake. Since several faults are overdue and closer to the next failure, an urgent update of the probabilistic seismic hazard map incorporating the impact of the great Tohoku earthquake is required.

REAL-TIME FORECASTING IN ITALY WITH ETES AND ERS MODELS

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The algorithms developed provide the users with quantitative estimates of the probability of occurrence of future earthquakes on specific areas of the target territory. The algorithms avail of the earthquake data detected by the Italian National seismic network. The software adopted for the estimation of the space-temporal seismic hazard is based on epidemic models of the ETAS type (Epidemic Type Aftershock Sequence). In these models each event can be either inducing another earthquake or induced by a previous one. The ETES model is a purely stochastic epidemic type earthquake sequence and the ERS model is physically constrained by the application of the Dieterich rate-state constitutive law to earthquake clustering.
The expected seismicity rate in any particular point of the target area for a given threshold can be determined through the contribution of all the previous events using a kernel function that involves: magnitude, distance, and time of occurrence of every previous event. The adopted magnitude distribution follows the Gutenberg-Richter law. The parameters used by the software have undergone a first phase of training using the INGV data set to obtain a maximum likelihood estimate of the parameters.
The software determines the occurrence probability of future moderate to large size events in Italy by the increase of seismicity rate detected in real time by the INGV seismic monitoring Center in Rome. We are able to do every 12 hours time-dependent maps of the expected rate density for a given magnitude threshold over the whole Italian territory.
The final map generated by the system is placed on a web page to be displayed. The user can zoom into a region in the area of interest for a study in detail. The user, for testing purposes, has the possibility to interact with the system to estimate the overall probability of an earthquake of magnitude greater than or equal to 4.5, in a specific interval of time and space in the whole territory. He can also decide whether to act on the size of the radius of the circle, within which the probability must be calculated. This option can be done by giving the geographical coordinates of the center of the area or by entering the name of the municipality.
The ETES model has been applied since 2006 in automatic way to the real time data (Murru et al., 2009). Moreover, a real application has started for the first time soon after the strong earthquake that stroke the City of L'Aquila (Central Italy) on April 6th, 2009 at 01:33 UTC (Mw $\geq$6.3). For a duration of some months, 24 hour earthquake forecasts produced in near real time through an algorithm based on the ETES model has been provided every morning to the Italian Agency of Civil Protection for their use in planning of rescue activities.
The seismic hazard modelling approach so developed is expected to provide a useful contribution to real time earthquake hazard assessment, even with a possible practical application for decision making and public information.

Reference

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CSEP-Japan : The Japanese node of the collaboratory for the study of earthquake predictability

Yokoi S., H.Tsuruoka, K. Z. Nanjo and N. Hirata
(ERI, Univ. of Tokyo)

Collaboratory for the Study of Earthquake Predictability (CSEP) is a global project of earthquake predictability research. The final goal of this project is to have a look for the intrinsic predictability of the earthquake rupture process through forecast testing experiments. The Earthquake Research Institute, the University of Tokyo joined the CSEP and started the Japanese testing center called as CSEP-Japan. This testing center constitutes an open access to researchers contributing earthquake forecast models for applied to Japan. A total of 105 earthquake forecast models were submitted on the prospective experiment starting from 1 November 2009. The models are separated into 4 testing classes (1 day, 3 months, 1 year and 3 years) and 3 testing regions covering an area of Japan including sea area, Japanese mainland and Kanto district. We evaluate the performance of the models in the official suite of tests defined by the CSEP.

The experiments of 1-day, 3-month and 1-year forecasting classes were implemented for 92 rounds, 6 rounds, and 3 rounds, respectively. On the 1-day testing class, all models passed all the CSEP's evaluation tests at more than 90% rounds. The results of the 3-month class also gave us new knowledge concerning statistical forecasting models. All models showed a good performance for magnitude forecasting. On the other hand, observation is hardly consistent in space-distribution with most models in some cases where many earthquakes occurred at the same spot. Throughout the experiment, it has been clarified that some properties of the CSEP's evaluation tests such as the L-test show strong correlation with the N-test.

In this presentation, we will overview CSEP-Japan and results of the experiments, and discuss direction of our activity. An outline of the experiment and activities of the Japanese Testing Center are published on our WEB site; http://wwweic.eri.u-tokyo.ac.jp/ZISINyosoku/wiki.en/wiki.cgi

Probabilistic Earthquake Forecasting: Statistical vs. Physical Models of Seismicity

M. J. Werner (Department of Geosciences, Princeton University, NJ, USA)

We review several recent applications of stochastic and physics-based models of seismicity for the purposes of long-term and short-term probabilistic earthquake forecasting. We begin with a study of the predictive power of five-year earthquake forecasts for California that are estimated by isotropically and adaptively smoothing the epicentral locations of declustered m>2 seismicity. These simple, objective and testable forecasts performed best during the five-year, prospective Regional Earthquake Likelihood Model (RELM) experiment in California. Their predictive skill is then compared with probability estimates based on adaptive space-time kernels, which circumvent the need for declustering prior to smoothing and perform slightly better than the adaptive space-only kernels. We also compare the performance of several short-term (next-day) models: an ETAS model implementation outperforms two flavors of a short-term space-time smoothing model and several flavors of a static Coulomb stress change model coupled with rate-state friction.

For a reasonable method of evaluating earthquake forecasts

Ken'ichiro Yamashina[1] and Tetsuto Himeno[2]

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Earthquakes sometimes occur in correlation with preceding events. However, such a correlation has not been considered in likelihood calculations or in the current Poisson-based tests adopted in the CSEP test centers to evaluate earthquake forecasts.

Table 1 presents the observed numbers of cells according to the frequency of earthquakes in a year based on the JMA data for the all-Japan area. Table 2 presents the inferred numbers of cells using retrospectively obtained values of expectation and the formulation of the Poisson distribution. Comparing with the observations in Table 1, it is clear that the results are extremely over- or underestimated. Consequently, a reasonable formulation of likelihood or some other evaluation test that does not employ the relation of the Poisson process, e.g., summation of square values of the difference between observed number and its expectation, is needed.

Table 1. Observed total numbers of cells of size 0.1° by 0.1°, in which earthquakes of magnitude 4 or greater occurred once, twice, three times, and so on per year in the all-Japan area from 2001 to 2010. Cases A, B, and C represent cells in which no events (A), one event (B), or two events (C) occurred in the previous years since 1965.

Data set	Cells affected	1	2	3	4	5	6	7	More
A(no events)	156,948	924	112	33	17	13	11	8	22
B(1 event)	21,561	498	59	10	10	7	1	0	5
C(2 events)	8,509	300	41	7	5	4	1	3	3
Total	187,018	1,722	212	50	32	24	13	11	30

Table 2. Inferred unreasonable numbers of cells in which earthquakes will occur once, twice, third times, and so on, using the numbers of cells affected and expectations obtained from the data for 2001 through 2010.

Data set	Cells affected	Expectation	1	2	3	4	5
A(no events)	156,948	0.01153	1789	10	0.04	0.0001	-
B(1 event)	21,561	0.03627	754	14	0.17	0.0015	-
C(2 events)	8,509	0.05864	471	14	0.27	0.0040	-
Total	187,018	0.01653	3041	25	0.14	0.0006	-

Regional and global earthquake forecast experiments within the Collaboratory for the Study of Earthquake Predictability

Jeremy D. Zechar (ETH, Zurich, Switzerland)

The RELM (Regional Earthquake Likelihood Model) working group designed a five-year experiment to evaluate earthquake forecasts in California. Each forecast specified the expected number of earthquakes in well-defined bins of latitude, longitude, and magnitude, and therefore we can quantify forecast consistency and compare forecasts. In subsequent earthquake forecast experiments within CSEP (the Collaboratory for the Study of Earthquake Predictability), researchers have applied this same approach in Italy, New Zealand, Japan, the western Pacific, and (as a proof-of-concept) the globe. I will present results from the RELM experiment in California, recently-completed one-year experiments in the western Pacific and the globe, and the ongoing one-day forecast experiment in California.

The majority of the experiment results I present will be based on measures of likelihood, but I will also introduce an intuitive round-robin gambling score comparison approach and describe the results of its application to the RELM experiment. I will also demonstrate how to build an ensemble earthquake forecast using Bayesian Model Averaging.

More generally, I will consider issues related to earthquake forecast experiment design, data quality, and an inclusive global earthquake forecast experiment.

Power of Relative Quiescence

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It is almost 30 years since Ogata(1983) introduced the maximum likelihood estimation method for the three parameters of Omori-Utsu formula, which describes the temporal decay of an aftershock sequence. It enabled us to investigate relative quiescence in aftershock sequences. We can judge the significance with aid of AIC. With those tools, I could judge quantitatively the relative quiescence of aftershock activity of the earthquake under waters of Hachijo-jima Island (Ms7.4 on 1972 Feb. 29) prior to the east off Hachijo-jima Island earthquake (Ms7.5 on 1972 Dec. 4). Ogata(1988) extended the time function of superposition of several main shock-aftershock sequences to ETAS model and showed some precursory relative quiescence was seen prior to many large earthquakes off Tohoku area in the catalogue for 95 years.

ETAS model freed us from any kind of declustering. With only five parameters, we can represent the temporal feature of complex seismicity in certain zone. ETAS model is also a powerful tool for swarm activities, in which μ is a function representing the effect of external force instead of the constant in the standard ETAS.

In 2007, the seismicity in off Tohoku district in Japan was quite low. JMA(2008) announced the quiescence was only one year in 2007 with some declustered data. However, with ETAS model, it was revealed that the relative quiescence appeared from 1998, and it lasted until 2008. It is the longest and the most significant relative quiescence in 126 years since 1885. Although we could not predict the occurrence of an M9 earthquake in the area before 2011 Mar. 11th, the relative quiescence could be detected in 2008, and it synchronized with the change in GPS data of the area. With the power of relative quiescence from the ETAS model, we have one element to expect a certain large earthquake.

Prediction Performance of Empirically Defined Foreshocks and Its Application to the 2011 Off Tohoku Earthquake

Kenji Maeda and Fuyuki Hirose (Meteorological Research Institute)

1. Introduction

Foreshocks have been thought one of the most promising phenomena to predict large earthquakes. However, foreshocks are mostly found after a large earthquake occurred and it is very difficult to distinguish them deterministically from background seismicity before a mainshock occurs. Therefore, empirical approach is one of the realistic ways to use foreshock activity as a precursor of a mainshock. We investigate probabilistic features of empirically defined foreshocks and search for the best parameters to define foreshocks which present relatively high performance to predict large earthquakes. Maeda (1996) once proposed a foreshock definition which gives relatively high performance to predict large earthquakes. We basically apply the same method as Maeda (1996) to the data from 1980 to 1993 using the new JMA hypocenter catalog in which the magnitude was revised in 2003, and reevaluate the parameters to define an effective foreshock activity. We also extend the data period from 1961 to 2011/3 and examine the stability of the best performance parameters.

2. Method

The method to search for parameters for foreshocks that present high prediction performance consists of four steps. 1) To use the data in which small aftershocks are eliminated. 2) To define a foreshock candidate as the activity that has number of Nf earthquakes with magnitude >= Mf during the period of Tf days in the segment of the size of D x D degrees^2 (latitude x longitude). 3) If a mainshock occurs in the period of Ta days after a foreshock candidate occurs, that candidate is treated as true foreshock(s). 4) To search for the values of Mf, D, Nf, and Ta which give high prediction performance by the grid search method. The prediction performance is measured mainly by dAIC, which is defined as the difference of AIC for a stationary Poisson model and a model using a foreshock activity, and additionally by alarm rate (AR: fraction of mainshocks alarmed), truth rate (TR: fraction of foreshock candidates followed by a mainshock), and probability gain (PG: ratio of mainshock occurrence rate for predicted space-time to background occurrence rate).

3. Data and Results

By applying the above method to the earthquakes cataloged by JMA for the period of 1980 – 1993 in the sea area of the northeastern part of Japan, we obtain the best parameters for foreshocks as Mf=5.0, D=0.5, Nf=3, and Ta=3 days to predict mainshocks with M>=6.0 for the fixed Tf=10 days. The prediction performance is expressed as dAIC=74, AR=13% (7/55), TR=19% (9/47), and PG=234. We also found that foreshocks defined above are observed only in the regions off Ibaraki, off Miyagi, and off Iwate prefectures. When we calculate the performance for these three regions, it is as high as dAIC=75, AR=58% (7/12), TR=38% (9/24), and PG=458. Next, we re-search for the best parameters of Nf and Ta for the longer period from 1961 to 2011/3, and we obtain almost the same best parameters of Nf=3 and Ta=4 days for the fixed Mf=5.0 and D=0.5. The performance is measured as dAIC=146, AR=8% (15/195), TR=13% (17/128), and PG=236 for all over the regions, and dAIC=125, AR=39% (12/31), TR=30% (14/47), and PG=363 for the above mentioned three regions.

4. Foreshock Activity before the 2011 Off Tohoku Earthquake

It is known that the 2011 Off Tohoku earthquake (M9.0) that occurred at 14:46 on March 11 was preceded by a foreshock activity. The mainshock is located in the off Miyagi region where the above mentioned foreshocks are expected. In 2011, earthquakes with M>=5.0 began to occur after middle of February near the mainshock epicenter. We search for the foreshocks defined above that are expected to give a best performance to predict a mainshock. Three earthquakes such as M5.2 at 18:53 on February 22, M6.3 at 06:22 on March 10 and M6.8 at 06:23 on March 10 are selected as foreshock candidates. Among them an M6.8 event is eventually a true foreshock, because the mainshock occurred within the predicted time window of 4 days and predicted area of 0.5 x 0.5 degree^2.

Reference

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Statistical Modeling of Seismicity Rate Changes in Oklahoma

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The rate of M>=3 earthquakes in Oklahoma substantially increased beginning in 2009 and continued through 2011 prior to the November M5.6 earthquake. We use standard statistical models and tests to investigate the significance and cause of this seismicity rate increase. Rate changes are often studied by declustering a catalog in an attempt to remove aftershocks and produce a set of event origin times that can be compared to a Poisson distribution. Instead, we use the Epidemic-Type Aftershock Sequence (ETAS) model, a stochastic model based on empirical aftershock scaling laws such as Omori's Law and the Gutenberg-Richter magnitude distribution, to detect whether this rate increase is due to an increase in the background seismicity rate, a change in the aftershock productivity, or some combination of these effects, given the past history of earthquake occurrence. We apply the ETAS model to the USGS PDE catalog of M>=3 earthquakes in Oklahoma occurring from 1973-2011 and find that a single set of parameters cannot fit the entire time period, suggesting that a significant change in the underlying process occurred in 2009. We find this by converting the origin times to transformed times and testing the null hypothesis that the transformed times are drawn from a Poisson distribution with constant rate, as one would expect where no external processes trigger earthquakes besides the tectonic loading rate. The null hypothesis can be rejected with p<0.001 based on an autocorrelation test and a Runs test which both show that successive interevent times are related to each other, which would not be true for a Poisson model. Next, we estimate ETAS parameters from the 1973-2008 data to determine which parameters must vary to fit the later data. Preliminary results suggest possible changes in both the background rate of independent events and the triggering properties. These tests may shed some light on whether these earthquake rate changes are natural or manmade.

Detecting misfits of the ETAS for seismicity anomalies

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The ETAS model provides a good estimate of earthquake intensity when the underlying mechanism is uniform. Any diversions of it from the data are hence to suggest anomalies, temporally or spacially, in the mechanism. Activation and quiescence caused by stress changes from outside would be one of such cases. Relatively long-lasting changes can be treated by the ETAS model with one or a few of change-points; in which framework all or part of ETAS parameters are estimated separately across those change-points. This method encounters troubles when a change occurs gradually over time or kicks in for a very short period of time, or appears repeatedly. For such troublesome data, we suggest the following misfit functions estimated by Bayesian smoothing.

We consider two forms of misfit functions. The first misfit function modifies the reference ETAS intensity by multiplying some numbers at each occurrence time of event.

$$\lambda'(t) = \lambda(t) \times q(t) \qquad \text{model1}$$

Any large diversions of *q(t)* from unity will suggest anomalies in seismicity. The second misfit function re-estimate the background portion of the ETAS intensity: *mu,* as a time-varying function *mu(t)* in the form

$$\mu(t) = \mu \times q(t). \qquad \text{model2}$$

We apply these misfit functions to several data to which simple change-point models are difficult to apply. The application includes those that contain swarm events, and some earthquake clusters triggered by the Tohoku earthquake of M9.0. Simulated data are also used to check the characteristics of these methods.

High fluid pressure and triggered earthquakes in the enhanced geothermal system in Basel, Switzerland

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The earthquake is a physical process releasing tectonically accumulated stress by shear faulting, controlled by Coulomb failure criterion. In order to understand earthquake generation, we need to know the pore fluid pressure in the Earth's crust as well as the stress state. Recently, we developed a new analysis technique, termed focal mechanism tomography (FMT), to infer 3D pore fluid pressure fields by examining the orientations of slip planes of seismic events within the prevailing regional stress field. In the present study we applied the method to 118 well-constrained focal mechanisms of seismic events triggered by the fluid injection experiment in the enhanced geothermal system in Basel, Switzerland. The Basel fluid-injection experiment provided an excellent opportunity to validate the FMT approach at the macro-scale because of the well-constrained regional stress field, the known fluid pressure history applied at the open section of the borehole, and numerous well-constrained focal mechanisms with relocated hypocenters. The inferred pore fluid pressure field of the stimulated region is consistent with known pressure history applied at the borehole. Elevated pore fluid pressures were concentrated within 500 m of the open hole section, and we found average earthquake triggering excess pore fluid pressures of about 10MPa above hydrostatic pressure. The triggering pore fluid pressures are substantially higher than that predicted from a linear pressure diffusion process from the source boundary, and shows that the system is highly permeable along flow paths to allow fast pressure diffusion to the boundaries of the stimulated region. Over-pressurized fluids induced many small events ($M < 3$) along faults unfavourably-oriented relative to the tectonic stress pattern, while the larger events tended to occur along optimally-oriented faults. This suggests that small-scale hydraulic networks, developed from the high pressure stimulation, interact to load (hydraulically isolated) high strength bridges that produce the larger events.

Statistic features of fluid-driven/related seismicities at different scales

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It is known that changes in stress induced by pore pressure diffusion and seismic rupture or any kind of deformation elsewhere, can lead to changes in seismicity even triggering large earthquakes. In the case of fluid-driven seismicity, earthquakes induced or triggered by fluid themselves produce changes in the local stress field that may result in self-triggering. Thus, it is important to be able to distinguish statistically between seismicity due to fluid diffusion and that due to self-triggering. Because the triggering process for a given fault system or earthquake sequence is complex and because it is difficult to precisely describe the transfer of stress in a fault system of fractal complexity, statistical approaches such as the epidemic-type aftershock sequence (ETAS) model, which incorporates the Omori law by assuming that each earthquake has a magnitude-dependent ability to trigger its own Omori-law-type aftershocks, have received significant attention.

In this presentation, several case studies concerning fluid-driven or fluid-related earthquakes at different scales are summarized. At core scale, as an analogy of earthquake, acoustic emission (AE) activity in stressed rock sample was used for investigating the role of pore pressure and drainage conditions on rock fracturing(Lei et al., 2011a). As a typical example of reservoir scale, the injection induced seismicity at the Rongchang gas field, in south-east border of Sichuan basin, China has been investigated (Lei et al., 2008). At regional scale, recent examples of reservoir triggered earthquakes and remotely triggered earthquakes, which are thought to be closely related with fluid, are examined (Lei et al., 2011b).

Results of these case studies indicate that the ETAS model aided with other statistic methods is a promising approach in terms of identifying fluid signals in seismicity patterns, even in the case of poor hypocenter data. The random component in the ETAS model can be considered as an indicator of fluid-driven activity, while the rate of Omori-law-type aftershocks indicates self-triggering of the preceding earthquakes. In general, fluid-driven seismicity at all scales shows following common features: 1) Normal or relatively small *b*-value, in contrast to earlier understanding; 2) More swarm-like characterized by smaller α in the ETAS model; 3) Progressive increase of the maximum magnitude; 4) Large events (M3+?) generally associated with pre-existing faults; 5) In case of fluid injection induced seismicity, the maximum magnitude of potential earthquake is determined by fault size not by the maximum fluid pressure.

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Relation between the slow slip that started since 2003 off Miyagi and Fukushima and the temporal variation of b-value

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1. Introduction

GPS analysis conducted by Meteorological Research Institute (2011, Yochiren) shows that a slow slip with M_w7.6 had occurred for 7 years from January 1, 2004 to January 1, 2011 on the plate boundary between the land and Pacific plates off Miyagi and Fukushima prefectures. It also seems that the slow slip had already begun in 2003 and the center of the slow slip moved from north to south. The slow slip locates in a southwestern deep part of the main rupture area of “the 2011 off the Pacific coast of Tohoku earthquake” and might be a pre-slip to the mainshock.

On the other hand, b-value of the G-R law (Gutenberg and Richter, 1944, BSSA) reflects the stress change occurring on fault planes of brittle rock in laboratory experiments (Scholz, 1968, BSSA). In this study, we investigated a relation between temporal variation of b-value and stress change associated with the slow slip before the 2011 Tohoku earthquake.

2. Data and Method

We used the JMA catalogue for the period from January 1, 1995 to March 10, 2011 with $M \geq 3.0$. Firstly, we extracted earthquakes which occurred in the Pacific interplate region and the upper part of double-planed deep seismic zone in the Pacific plate from the catalogue taking into consideration the tectonic conditions by using REASA (Aketagawa et al., 2007). Secondly, we divided the analysis area into four areas taking into consideration seismicity also: Area “A” which is northern neighbor of the slow slip; “B” which is northern part of the slow slip; “C” which is southern part of the slow slip; and “D” which is southern neighbor of the slow slip.

We estimated the temporal variation of b-value by using REASA. We set 200 events as the calculation unit in order to estimate the temporal variation of b-value and shifted them at every 50 events. We estimated the b-value for events larger than M_c by the maximum likelihood method (Utsu, 1965, Hokkaido Univ.), where M_c is a lower limit magnitude and was fixed at 3.0 during the whole period.

3. Results and Discussion

The following results are obtained.

1) In the area A, a northern neighbor of the slow slip, b-value had decreased over time little by little from 2002 to 2011.
2) In the area B, a northern part of the slow slip, b-value had decreased with time in 2002–2005 and it increased slightly with time until 2008. After that, it decreased again.
3) In the area C, a southern part of the slow slip, b-value varied vibratingly.
4) In the area D, a southern neighbor of the slow slip, b-value decreased with time and suddenly plunged in 2008 and then recovered to the previous level.

Considering the inverse correlation between b-value and stress obtained in laboratory experiments (Scholz, 1968, BSSA), we can assume that stresses applied to the area A increased with time in 2002–2011 because b-value decreased with time. It is reasonable that stresses applied to the area A increased due to occurrence of the slow slip at neighbor area B. Most of background seismicity in the area B occurred in the margin of the slow slip in 2002–2005 where stress increase is expected. Therefore, b-value decreased at that period. As slow-slip area spread over the area B after 2005, the overall stresses applied to the area B fell down (b-value increased). After that, the stresses of the area B increased (b-value decreased) again because the slow slip moved to the south. Stresses (b-value) in the area C varied vibratingly. This is probably because the stress change caused by a moving slow slip affects the seismicity of clusters differently in the area. Since the slow slip of the area C accelerated in 2008, stresses in neighbor area D also accelerated (b-value decreased suddenly). Then stresses were released (b-value increased) by occurrence of comparatively large earthquakes in the area D. That is to say, these observations suggest the possibility that variations of b-values reflect the stress change induced by the slow slip before the 2011 Tohoku earthquake on the plate boundary off Miyagi and Fukushima.

Triggered non-volcanic tremor in SW Japan, by the 2011 Tohoku earthquake and its aftershocks

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The March 11, 2011 M9.0 Tohoku earthquake was followed by large aftershocks and broad seismic activation both inland and offshore Japan (e.g., Hirose et al., 2011; Ogata, 2011; Toda et al., 2011). Previous studies (Enescu et al., 2011; Miyazawa, 2011; Obara and Matsuzawa, 2011) reported remotely triggered seismicity at distances up to about 1350 km from the mainshock. Deep non-volcanic tremor in south-west Japan (Obara, 2002) was also clearly activated following the Tohoku earthquake. We focus here on the detailed analysis of the triggered tremor.

We detect tremor that correlates with the passage of the mainshock surface waves at several Hi-net seismic stations in Shikoku region, at distances of about 1000 km from the Tohoku earthquake epicenter. We use an envelope cross-correlation technique to locate the tremor sources. The best tremor location is determined using a 3D grid-search that minimizes the residuals between observed and calculated travel time differences at pairs of recording stations. While the depth of the tremor source is not well constrained by our grid search, the signal originates from a deep source in the lower crust. Our location results show that the mainshock triggered tremor in two distinct areas, in western and central Shikoku, in regions where ambient (i.e., not triggered) tremor occurs (e.g., Obara et al., 2010). The triggered tremor in western Shikoku also occurs close to the tremor triggered by previous large, remote earthquakes (e.g., Miyazawa and Mori, 2006).

We have also detected triggered tremor during the passage of the incoming surface waves from the earliest aftershock (M_{JMA}7.4) of magnitude above 7.0, which occurred about 23 min. after the mainshock, as well as from the largest aftershock (M_{JMA}7.7) that occurred about 30 min from the mainshock. However, we did not find any evidence of triggered tremor by the M_{JMA}7.3 foreshock, occurred on March 9th, 2011.

We have estimated the peak dynamic stresses during the passage of surface waves from the mainshock and the two aftershocks, using the observed peak ground velocity at nearby F-net and KiK-net stations. The obtained values are roughly between 10 KPa and 180 KPa (the upper value corresponds to the mainshock), higher than the apparent triggering threshold found in this and other regions (Chao et al., 2011).

We have checked whether the detected tremor was triggered by the passage of the Love or Rayleigh waves from the Tohoku mainshock and its aftershocks. Our results indicate that the Love waves were the main triggering factor. The tremor triggered by the mainshock and the M_{JMA}7.4 aftershock, in particular, correlate well with the Love waves cycle. Our results are consistent with theoretical modeling that shows that Love wave displacement to the south-east (sea-ward) would promote up-dip shear on the plate interface in the Shikoku region (Hill, 2010). In a related study, Chao et al. (2011) report Love wave triggering in Shikoku by other remote earthquakes. While the triggering by Rayleigh waves in south-west Japan has been well documented (e.g., Miyazawa and Mori, 2008), our recent work shows for the first time clear evidence of Love wave triggering in the region.

Change in seismicity rate around 100 major late Quaternary active faults due to the 2011 off the Pacific coast of Tohoku, Japan Earthquake

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Significant changes in seismicity rate are observed for fault zones in Tohoku and Central Japan due to the 2011 off the Pacific coast of Tohoku, Japan Earthquake with a magnitude (M) of 9.0 on the Japan Meteorological Agency scale (M_{JMA}). Some fault zones are well explained by the Coulomb stress changes due to the mainshock. However, changes in seismicity rate around the other fault zones are inconsistent with the Coulomb stress changes imparted by the giant earthquake and calculated on the major fault zones. We investigated changes in seismicity rate around about 100 major active fault zones which are selected by the Headquarters for Earthquake Research Promotion.

Occurrences of large earthquakes concentrate on a time interval, several years before and 10 years after an occurrence of a large (giant) interplate earthquake along the Japan trench (Shimazaki, 1978). For example, Rikuu earthquake (M7.2) occurred two and half months after the 1896 Meiji Sanriku earthquake. Swarm activity was observed in the Rikuu earthquake source region after the Meiji Sanriku earthquake (Imamura, 1913). It is important to examine changes in seismicity rate in order to infer an effect on large earthquakes occurring on major fault zones.

In this study, we extracted earthquakes which occurred within 5-km distance from a fault plane from March 11, 2010 to November 11, 2011, and calculated changes in seismicity rate. Furthermore, we examined the consistency with the Coulomb stress changes due to the mainshock and afterslip (Earthquake Research Committee, 2011).

Seismicity rate increased more than 10 times for 11 fault zones (i.e., the Sakai Toge/Kamiya (Main), Kita-Izu, Mahiru-Sanchi Toen, Nagamachi-Rifusen, Yokote-Bonchi Toen, Nagai-Bonchi Seien, Takada-Heiya Toen, Tokamachi (West), Muikamachi (South), Inohana fault zones, and Gofukuji fault).

Among these, changes in seismicity rate around the Tokamachi, Muikamachi, and Takada-Heiya Toen fault zones are contaminated by the occurrence of the M_{JMA} 6.7 earthquake on March 12. Swarm activities have been observed after the mainshock near the Nagamachi-Rifusen and Nagai-Bonchi Seien fault zones and it is necessary to examine the association between these swarms and the fault zones. The Sakai Toge/Kamiya, Kita-Izu fault zones, and Gofukuji fault are consistent with the increases of the Coulomb stress. Around the Gofukuji fault, M_{JMA} 5.4 earthquake occurred on June 30. On the other hand, increases in seismicity rate are inconsistent with the Coulomb stress changes calculated for the Mahiru-Sanchi Toen, Yokote-Bonchi Toen, and Inohana fault zones. The Coulomb stress changes are small for the Inohana fault zone although the absolute value is dependent on the apparent coefficient of friction. For the Mahiru-Sanchi Toen and Yokote-Bonchi Toen fault zones, seismicity rates increased regardless of decreases in the Coulomb stress. Focal mechanisms of earthquakes which occurred after the mainshock are dominantly strike-slip even though the thrust-type is dominant before the mainshock. The distribution is complementary with the distribution of earthquakes which occurred before the mainshock. Thrust type of earthquakes such as the aftershock area of the 2008 Iwate-Miyagi earthquake (M_{JMA} 7.2) drastically decreased after March 11 in Tohoku region, and this is well explained by the extension in the E-W direction due to the mainshock. These results imply that the stress field in the crust is originally heterogeneous in space.

Other factors will also change seismicity rate. Especially, dynamic stress changes will strongly affect changes in seismicity rate just after the mainshock. Declustered catalog may be more appropriate in order to estimate the change in background seismicity rate.

BIAS IN FITTING THE ETAS MODEL: A CASE STUDY BASED ON NEW ZEALAND SEISMICITY

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We fit various forms of the ETAS model to a large region that includes all of the most seismically active areas of New Zealand. The ETAS model contains two components: a component describing background or immigrant events, and a part describing aftershocks of the background events and aftershocks of the aftershocks. We refer to the first part as the background part and the second as the ETAS part. Generally all of the sophistication, and the bulk of the model parameters, lies in the ETAS part of the model. The background component is generally treated as a nuisance component and is often very simplistic. While the main interest lies in the ETAS part of the model, the poor model description of the background part imposes considerable bias on the ETAS part of the model. For example, a poorly specified spatial density of the background events causes many of the background events to be seen as ETAS events. It can also cause the estimated Omori powerlaw decay p to be too small, and hence the aftershock sequences appear to continue for a too longer time. On the other hand, the boundary of the observation region can impose a reverse bias which causes aftershocks that are close but within the boundary to be seen as background events.

In almost all of the large NZ event sequences since 1965, the model consistently under-fits these sequences. Consequently, it over-fits those space-time regions where there is “normal” seismicity with no major events present. This may indicate that the space-time region of a major event sequence is much closer to criticality, in that aftershock events appear to be much more easily initiated. The standard ETAS model does not reflect this observation.

Repeating Earthquake Recurrence Intervals: Magnitude and Time-Dependence

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An idealized definition of a repeated earthquake is an earthquake that identically ruptures the same fault patch (or segment) as that ruptured by an earlier earthquake. As a consequence, the two earthquakes have identical magnitudes, locations, and waveforms. Together the two earthquakes are called repeating earthquakes. In nature, however, the 'identical' properties of repeating earthquakes are only approximately realized, and in practice events having 'similar' magnitudes, locations, and waveforms are typically referred to as repeating or characteristically repeating earthquakes. A time ordered series of two or more repeating earthquakes is called a repeating earthquake 'sequence', and the times between sequential events the sequence are the sequence event recurrence intervals. The magnitude and location of a given sequence are commonly taken to be the average magnitude and location of the events in the sequence.

Repeating earthquake sequences have been observed over a wide range of sequence magnitudes and in a variety of tectonic environments, including strike slip boundaries in California and Turkey, subduction zones in Japan, South America and Cascadia, and on oblique thrust faults in Taiwan. The recurrence intervals of repeating earthquakes scale with magnitude, but are also strongly dependent on the tectonic loading rate of the faults on which they occur. When normalized for differences in loading rate, however, the magnitude scaling of their recurrence intervals is remarkably consistent among tectonic environments and over a range of magnitudes extending from at least M-0.7 to M7.4.

In this presentation, the scaling properties of repeating earthquakes will be discussed, and the variability of repeating event recurrence intervals will be examined in the context of time-dependent tectonic processes along the San Andreas Fault in central California. In particular we find that near moderate to large earthquake rupture zones, recurrence intervals preceding the earthquakes are longer than expected and intervals after the events are initially shorter and progressively lengthen. In regions well away from the larger earthquakes, we also find significant intermediate-term (months to years) modulations in recurrence intervals that are coherent among sequences separated by up to 10s of kms. These modulations, in conjunction with the dependence of recurrence intervals on loading rates, support the view that incorporation of geodetic information into time-dependent earthquake forecast models can significantly improve their accuracy.

Space-Time Models of Repeating Earthquakes in Parkfield Segment

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We propose a space-time model for many sequences of repeating earthquakes whose hypocenters are distributed in a plane. Nadeau et al. (1995) discovered many series of earthquakes with almost the same hypocenters and seismic waves in Parkfield segment of San Andreas fault, California. They recurred very regularly and therefore renewal processes can be applied better than Poisson processes as a stochastic model of the repeating earthquakes. But when we apply a renewal process to these sequences, we will confront with the problem that the inter-event times have some trends which develop by time. These changes of the recurrence intervals are related to the changes of the slip rate near their hypocenters, and Nadeau and McEvilly (1999) estimated the space-time changes of the slip rate in Parkfield segment from their dataset.

In our study, we assume the stress loading process by Matthews et al. (2002), composed by stress loading rate and its perturbation represented by an Brownian motion, and estimate the space-time changes of the stress loading rate by a non-stationary renewal process. If the stress loading rate is constant, repeating earthquakes occurs along to a renewal process with the Brownian Passage Time (BPT) distribution. But we assume the stress loading rate changes by its location and time, and extend the renewal process to a non-stationary renewal process by time-transformation with the loading rate. The change of the stress loading rate in space and time is represented by smooth spline functions allocated to the partitioned grids. On estimating the spline function, we incorporated a penalty function for unsmoothness into the model to avoid overfitting to the dataset.

Thus, we analyzed the dataset of repeating earthquakes provided by Robert M Nedeau. This dataset contains the occurrence data both before and after 2004 M6.0 earthquake in Parkfield. We divided the dataset at this large earthquake for our analysis. The same feature as Nadeau and McEvilly (1999) pointed out for the change of slip rate are seen in our results, and also the effects of other larger earthquakes exceeding M4 are seen in some of the repeating sequences. After the M6.0 earthquake, its aftershocks appeared at those sequences, but their decay rates differs among the repeating sequences. The prominent changes in stress loading are occurred during 50 to 100 days elapsed from the main shock, around the M9.1 earthquake in Sumatra.

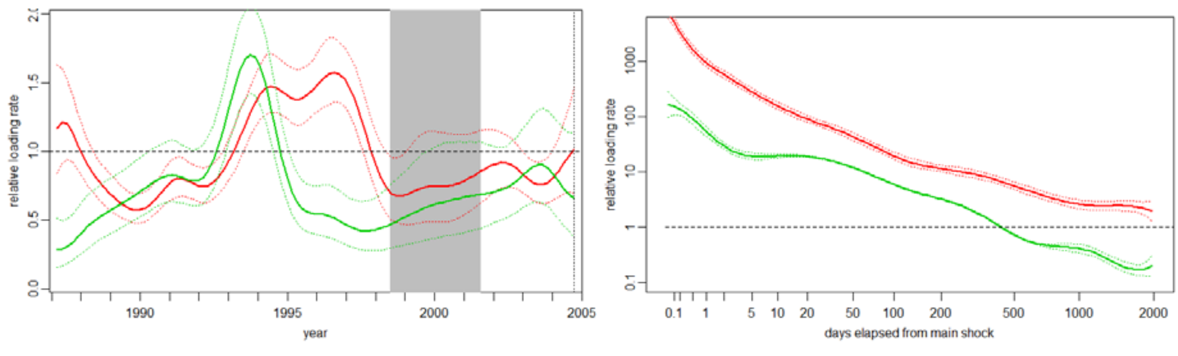

Figure: Relative loading rates from their reference rates (left) before and (right) after 2004 M6 earthquake. The red and green curves correspond to the sequences in shallow and deep zone.

Repeating earthquake activity before and after the 2011Tohoku earthquake

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1. Introduction

A diversity of seismic events including megathrust, tsunami and intraplate earthquakes have occurred in the northeastern Japan subduction zone. Small repeating earthquakes, which have been found in this subduction zone and other plate boundaries, are significant because they indicate recurrent rupture of small asperities on a plate boundary. They are used for the study of interplate quasi-static slip, earthquake cycle, nature of asperities, structure changes and statistical modeling of earthquake recurrence etc. In this study, we detected repeating earthquake before and after the 2011 Tohoku earthquake (M9.0) and discuss on the activity change and spatio-temporal distribution of quasi-static slip.

2. Data and Method

We analyzed waveform data for the period from 1984 to 2011 to find repeating earthquakes. The sampling frequency was 100Hz and most of the seismometers were of 1Hz velocity type. We selected earthquake pairs with epicenter separations of less than 30km and calculated cross-spectrum for a 40s window containing both P and S waves. The criterion for selecting repeating earthquakes was set that the averaged coherence at 1-8Hz must be larger than 0.95 for small repeating earthquakes (M>=2.5, Uchida et al. (2006)) and averaged coherence around the corner frequency must be larger than 0.8 for moderate sized repeating earthquakes (M>=4.0, Uchida et al., 2010).

The cumulative slip of repeating earthquakes which represent interplate quasi-static slip are estimated by using an empirical relationship between seismic moment and slip proposed by Nadeau and Johnson (1998). We also examined the spatial distribution of repeating earthquakes and magnitude difference of repeating earthquakes before and after the 2011 Tohoku earthquake.

3. Results

The repeating earthquakes are located mainly outside the area of large coseismic slip for the 2011 Tohoku earthquake. However there are some groups at the moderate to small coseismic slip area of the M9 earthquake. This show the coseismic slip area are not 100% coupled before the M9 earthquake.

From the cumulative slip of repeating earthquakes, high slip-rate was observed in the afterslip area of a M7.3 earthquake that occurred two days before the Tohoku earthquake. We also found higher slip rate at the updip (shallower part) of earthquake source area in 2008. The north-south extent of this high-slip rate corresponds to the slip extent of the 2011 earthquake and such slip was not detected prior to 2008.

After the 2011 Tohoku earthquake, we found clear afterslip from moderate sided repeating earthquakes. The afterslips occurred mainly outside the slip area for the 2011 earthquake and maximum slip of about 1.2m in 9 months was estimated to the northwest of the coseismic slip area. The slip history also shows that slow rise of slip acceleration occurred at the area relatively far from the coseismic slip area. This probably shows slip migration from the region close to the coseismic slip area to the regions surrounding the area.

In the slip area of the 2011 earthquake, almost all repeating earthquake stopped to occur after the earthquake. In addition, the repeating earthquakes at the deeper extension of the coseismic slip for the M9 earthquake had larger magnitudes than before. This area is also characterized by high repeating earthquake activity after the earthquake. These observations probably related to the stress release by the 2011 earthquake, the change of fault property and the afterslip at the deeper extension of the coseismic slip area.

4. Conclusions

1. Quasi-static slip distribution for 18 years show preceding the 2011 Tohoku earthquake, there was small slip rate increases in 2008 and 2011 at off Fukushima and Miyagi that are located near the 2011 M9 earthquake's slip area.

2. The afterslip of the 2011 Tohoku earthquake was observed mainly outside of the coseismic slip area. The slip increased sharply for the locations close to the large coseismic slip area while it incleased slowly for the areas far from the slip area.

3. The repeating earthquake activity including the spatial distribution and averaged magnitude are changed after the 2011Tohoku earthquake.

A Bayesian model, Negative Binomial Model, for forecasting major aftershocks

Masami OKADA (guest researcher, MRI)

Introduction. A Bayesian model, Negative Binomial Model, has been proposed by Okada and Ito (2001) for estimating the magnitude of largest event and the number of major events in the aftershock sequence in forthcoming period. As the model has no unknown parameter, it is useful to calculate those distributions even just after the main shock.

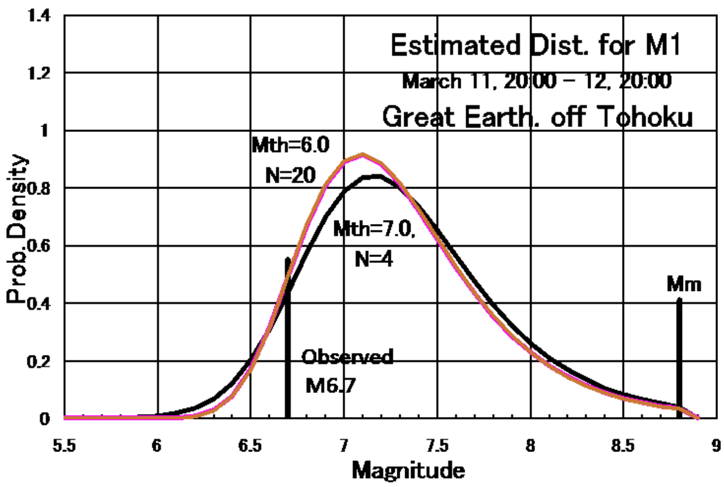
Model. From Gutenberg-Richter law and Omori-Utsu law, the rate, λ, of aftershocks with Magnitude M and time t can be expressed as

$$\lambda(M, t) = A \times \beta \exp\{\beta(M_m - M)\} \times \frac{(t + c)^{-p}}{c^{-p+1} - (t_{\max} + c)^{-p+1}}.$$

Here M_m is the magnitude of main shock, and $t_{\max}$ is the maximum elapsed time for analysis. The A-value fluctuate widely by sequence by sequence, but others, β, p, and c are fairly stable, therefore we treated the parameter A as a random variable obeying a gamma distribution and the others as common values in any sequence. The β-, p-, and c-values are determined by superimposing many aftershock sequences.

In this model the number of aftershocks with $M_{th} \le M \le M_m$ and $0 \le t_1 \le t \le t_2 \le t_{\max}$ follows a negative binomial distribution. The distribution of magnitude difference, D_1, between the main shock and the largest aftershock, corresponding the magnitude of the largest aftershock, is derived from a relation, $\Pr\{D_1 \ge d\} = \Pr\{N_{event} = 0 | M_{th} = M_m - d\}$. The posterior distribution of A is also gamma easily calculated, when the number of events with $M_s \le M \le M_m$ is given for the observation period, $t_s \le t \le t_p$. Using the posterior distribution, we estimate the distributions for the magnitude of the largest aftershock and the number of major events with $M_{th} \le M \le M_m$ in the coming period, $t_p \le t \le t_f$.

Example. The JMA distributed a copy of figure for media on that day of the Great Earthquake off Tohoku which showed the distribution of main shock and major aftershocks in about five hours after main shock. The main shock was written as M8.8, and locations of 26, 16, and 3 aftershocks with $5.0 \le M \le 5.9$, $6.0 \le M \le 6.9$, and $M \ge 7.0$ are shown in the figure, respectively. Right figure shows the magnitude distribution for the largest aftershock in the following 24 hours retrospectively forecasted from the observation data.



PI forecast with or without de-clustering: an experiment for the Sichuan-Yunnan region

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Since aftershocks contribute to a large extent to the total number of earthquakes, whether de-clustering affects the performance of the earthquake forecast is one of the concerns in the application of the statistical seismology algorithms. We analyzed the PI forecasts for the Sichuan-Yunnan region of southwest China in which there occurred some earthquakes larger than M_S7.0, including the 2008 great Wenchuan earthquake. In the analysis, time-space epidemic-type aftershock sequence (ETAS) model and stochastic declustering method was used for the de-clustering.

We analyzed the background and clustering seismicity of earthquakes above M_L3.0 in the period from 1977 to the day before the Wenchuan M_S8.0 earthquake, and PI algorithm was revised to consider de-clustering, by replacing the number of earthquakes by the sum of the ETAS-assessed probability for an event to be a 'background event' or a 'clustering event'. The result shows that generally de-clustering has little effect on the performance of PI forecast. However, case studies indicate that after an intense aftershock sequence is included in the 'sliding time window', hotspot picture may vary, and the variation lasts for about one year. PI forecasts seem to be affected by the aftershock sequence included in the 'anomaly identifying window', and the PI forecast using 'background events' needs shorter time to recover from the effect of the aftershock sequence.

Daily variation of the detection capability of earthquake and its influence on the completeness magnitude

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Evaluating the detection capability of earthquakes in an earthquake catalogue is the first step of statistical seismicity analysis. Conventionally the completeness magnitude *Mc*, the minimum magnitude of complete recording, is estimated for a catalogue ranging over several weeks, months or years [e.g., Wiemer and Wyss, 2000, BSSA]. It is well known, however, that the detection capability of earthquakes is lower in daytime than in nighttime because of human activity [e.g., Rydelek and Sacks, 1989, BSSA; Atef et al. 2009, BSSA];, and hence an estimated *Mc* for a catalogue ranging over more than one day would be smaller than *Mc* in daytime. Therefore, a quantitative analysis of daily variation of detection capability is necessary to discuss the completeness of an earthquake catalogue.

In this study, we used a statistical model representing a magnitude-frequency distribution of all observed earthquakes [e.g., Ringdal, 1975, BSSA; Ogata and Katsura 1993, GJI]. The distribution was assumed to be the product of the Gutenberg-Richter (GR) law and a detection rate function $q(M)$. Following the previous studies, the cumulative distribution of the normal function was used as $q(M)$. Hence, $q(M)$ has two parameters μ and σ. In the evaluation of the detection capability, the parameter μ is fundamental, and it indicates the magnitude where the detection rate of earthquake is 50%. By combination of and μ and σ, we can compute the magnitude where the detection rate is equal to a particular probability.

Data used in this study was taken from the JMA catalogue from 2008 to 2010. Subareas covering whole of the inland of Japan with a size of 1 x 1 degree were considered, and sequences of shallow (depth ≤ 30 km) were constructed for each of the subareas. The earthquake sequences were divided into one-day increments, and divided sequences were stacked in each of the subareas. Then, a Bayesian approach with a piecewise linear function and smoothness constraint [Iwata, 2008, GJI; 2011, Research in Geophysics] was applied to these stacked data to estimate the daily variation of μ in each of the subareas. The value of σ and the *b*-value of the GR law were also estimated through the framework of the maximum likelihood method.

In this study, the value of $\mu+3\sigma$, corresponding to the magnitude where the detection rate is approximately equal to 99.9%, was regarded as the completeness magnitude. In most of the subareas, the value of $\mu+3\sigma$ is close to 1 or less than 2, which is consistent with Nanjo et al. [2010, BSSA] investigating *Mc* in Japan using the 1-year JMA catalogue. In a few subareas, however, the value of $\mu+3\sigma$ exceeds 2, suggesting that, to ensure the completeness of an earthquake catalogue, it is important to consider the daily variation of the detection capability.

On the criticality of branching models for earthquake occurrences

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The ETAS model has been widely accepted as a standard model for describing clustering characteristics of earthquake occurrences. Several versions of this model have been proposed and applied in the studies on seismicity in different regions from worldwide. Model parameters are usually estimated by maximum likelihood estimate (MLE) or the expectation-maximization (EM) algorithm. The estimated model parameters vary from case to case, sometimes even irrational. To justify the reasonability of the outputs from fitting the modal to some earthquake datasets, we need a good understanding to the stability conditions of the ETAS model. Also, any extensions or specifications of an explicit branching modal for seismicity should take into consideration these stability conditions. Such conditions are closely related to the concepts of the criticality and the branching ratio of the model.

In this study, we start with a more general form of branching models with the following assumptions: (1) The mean number of direct children produced by an event of magnitude m' is a Poisson random variable with a mean of $\kappa(m')$; (2) The magnitudes of the children from a parent of magnitude m' are i.i.d. r.v.s with a density $s(\cdot \mid m')$; and (3) The magnitude p.d.f. for the background events is $s_0(m)$. The *criticality* parameter summarizes the asymptotical behavior of the population in the infinitely large generation, determined by the maximu eigenvalue ϱ of the eigenequations

$$\varrho\, a(m') = \int_{\mathcal{M}} a(m)\, \kappa(m)\, s(m' \mid m)\, dm$$

and

$$\varrho\, b(m) = \int_{\mathcal{M}} \kappa(m)\, s(m \mid m')\, b(m')\ dm' .$$

The *branching ratio* ω is defined by the proportion of triggered events in all the events. When the process is stationary and ergodic,

$$\omega = \int_{\mathcal{M}} \kappa(m)\, s_1(m)\, dm$$

where $s_1(m)$ is the magnitude density for all the events. That is, the branching ratio is also the average number of events that is triggered by an arbitrary event.

For the ETAS model, the magnitude density is completely separable from the whole intensity, and the branching ratio is identical to the criticality parameter. Based on these results for general cases, we also reveal some problematic issues related to the BASS model. Especially the G-R law is not satisfied any more.

On the frequency-magnitude distribution of converging boundaries

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Here, we show some detailed statistical analysis of a database of worldwide interplate earthquakes occurring at current subduction zones. This database provides a unique opportunity to explore in detail the seismogenic process in subducting lithosphere. In particular, the statistical analysis of this database allows us to explore many interesting scientific issues such as the existence of different frequency-magnitude distributions across the trenches, the quantitative characterization of subduction zones that are able to produce more likely mega-thrust earthquakes, the prominent features that characterize converging boundaries with different seismic activity and so on. Besides the scientific importance, such issues may lead to improve our mega-thrust earthquake forecasting capability.

Development of Tool for SEISmicity Analysis: TSEIS and Future scope

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A tool for seismicity analysis is updated from original software that is only running under Solaris system to new one that is available under Unix, Windows and MacOSX. The software is written by standard GNU compilers of gcc and gfortran that is widely distributed and is in operation under many kinds of operating systems. This tool has functions of 1) macro command, 2) customizable menu, 3) web interface and 4) ETAS algorithm analysis and etc. The new system is more convenient and powerful for users with the help of graphical user interface, and is welcomed to usage for researchers in the field of seismicity. The web version of this system is accessible at http://wwweic.eri.u-tokyo.ac.jp/tseis/ or http://wwweic.eri.u-toyo.ac.jp/db/.

Earthquake Research Institute operates 12 testing classes of Collaboratory Study for Earthquake Predictability. As we are now using testing system of CSEP Suits mainly developed by SCEC, we need a tool to check the performance of predictions of earthquake models easily and directly. We will have a plan to add such functions to this system in the near future.

Japanese National Research Program for Earthquake Prediction and the earthquake forecast testing experiment with statistical seismology

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The Japanese national earthquake prediction program started in 1962 with a blue print for the scope and direction of research to follow. Substantial time and efforts were subsequently devoted to the construction of new observation networks and the study on the earthquake generation mechanisms. An important result has been the recognition of the great difficulty in identifying creditable precursors due to a diversity of earthquake generation process. The new national program, which inherits its essential observational network from all the previous programs, emphasizes the importance of modeling as well as monitoring for a sound scientific development of earthquake prediction research [1].

One major focus of the current program is to move toward creating testable earthquake forecast models. For this purpose, we joined the Collaboratory for the Study of Earthquake Predictability (CSEP) and installed, through an international collaboration, the CSEP Testing Centre, an infrastructure to encourage researchers to develop testable models for Japan and to conduct verifiable prospective tests of their model performance. In 2009 we started the 1st earthquake forecast testing experiment for the Japan area within the CSEP framework [2].

The experiment consists of 12 categories, with 4 testing classes with different time spans (1 day, 3 months, 1 year and 3 years) and 3 testing regions called "All Japan," "Mainland," and "Kanto." A total of 105 models were submitted, and are currently under the CSEP official suite of tests for evaluating the performance of forecasts. I will give an idea how good results we will have. Our aim is to describe what has turned out to be the first occasion for setting up a research environment for rigorous earthquake forecasting in Japan. The statistical seismology, including Professor Ogata's contribution to the CSEP Japan testing experiment, is essential to enrich our activities.

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Systematic Errors in the Inversion Analysis of GPS Array Data to Estimate Interseismic Slip-deficit Rates at Plate Interfaces

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The occurrence of earthquakes is the sudden release of tectonically accumulated stress by faulting. In the case of interplate earthquakes, the stress accumulation is caused by the interseismic increase of slip deficit in source regions. The crustal deformation due to the interseismic slip-deficit increase is now detectable by GPS measurements. Here we consider the problem of estimating interseismic slip-deficit rates at plate interfaces from observed GPS velocity data with a model based on elastic dislocation theory. In this problem, first, we subtract theoretical surface velocities due to known steady relative plate motion from the observed GPS data, and presume the residuals to be caused by slip deficit at plate interfaces. However, the Earth's crust includes a number of defects such as micro cracks and active faults. Interseismic brittle fracture and/or plastic flow at these defects cause the translation and rotation of local crustal blocks, which cannot be explained by the interplate slip-deficit model [1]. If observed data contain theoretically unexplainable coherent noise (systematic errors), the result of inversion analysis will be seriously biased. One of the ways to remove the effects of rigid body translation and block rotation from GPS array data is to transform observed horizontal displacement vectors into average strain tensors for individual triangles composed of adjacent GPS stations [2]. By this transformation, original information about intrinsic deformation is preserved. Applying an inversion formula based on Bayesian statistical inference theory [3] to the GPS strain data, we can obtain unbiased slip-deficit rate distribution. We demonstrate the applicability of the GPS strain data inversion method through the analysis of interseismic GPS velocity data (1996-2000) in the Japan region [2,4,5], where the North American, Pacific, Philippine Sea, and Eurasian plates are interacting with each other in a complicated way.

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Modelling and analysis of foreshock sequences: can we identify anomalous aseismic deformation related to the nucleation of major earthquakes?

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Foreshock activity characterizes many major, destructive earthquakes. It has been argued that such activity could be related to aseismic deformation, perhaps linked to precursory slip by the main asperity, or, as for example in the case of the 1975 Haicheng earthquake, to fluid-related unclamping of the fault zone. However, ETAS models have shown that, on average, an acceleration of the seismicity rate is obtained before any earthquake, owing to 'normal' earthquake interactions (i.e., those respons ible for the emergence of the Omori-Utsu law). These two explanations of foreshock activity (either due to an anomalous, transient aseismic forcing, or to the 'normal' cascade of triggering) have been proposed in many studies of historical sequences. One major difference between these two treatments is that the 1st generally examine the spatial proximity of the earthquakes (e.g., through stress calculations) but not the time delays between the events, while the 2nd is mostly purely temporal. We here describe a stochastic model that accounts for both earthquake interaction processes and possible aseismic forcing transients, that allows to quantify the relative contributions of these two phenomena in generating foreshock activity. We apply this model to the 2-day long foreshock sequence preceding the 2011, Tohoku earthquake. The importance of accounting for both the spatial and temporal 'locations' of the foreshocks relative to the mainshock is particularly investigated.

Detection and modeling of seismicity driven by transient aseismic processes

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It is widely accepted that the Coulomb failure stress variations are underlying earthquake activity. Usually two components of stress variations are considered, the slow and stationary stress build-up due to tectonic forcing and static stress changes related to earthquake occurrences. In this case, the epidemic-type aftershock sequence (ETAS) model has been shown to describe successfully the spatiotemporal evolution of the statistical properties of seismicity. However, in many cases, seismicity might be locally dominated by stress changes related to transient aseismic processes such as magma intrusion, fluid flow or slow slip events which are not directly observable in general. Therefore, it is important to account for those potential transients, firstly to avoid erroneous model fitting leading to biased forecasts and secondly to retrieve important information about the underlying transient processes. In this work, we apply a recently developed methodology to identify the time-dependent background-term which is based on iteratively applying a ETAS-based declustering where the size of the internally applied smoothing filter is set by the Akaike information criterion. This procedure is shown to work well for synthetic data sets. We find that the estimated model parameters are biased if the time-dependence is not taken into account. In particular, the alpha-value describing the magnitude-dependence of the trigger potential can be strongly underestimated if transients are ignored. Low alpha-values have been previously found to indicate swarm activity which is often related to transient processes. Thus observed anomalous alpha-values might refer to transient forcing rather than to differences in the earthquake-earthquake trigger mechanism. To explore this, we apply the procedure systematically to earthquake clusters detected in Southern California and to earthquake swarm data in Vogtland/Western Bohemia. We identify clusters with significant transient forcing and show that low alpha-values are not always artificial and thus might indicate a mechanically different earthquake-earthquake interaction mechanism.

Delaunay-based Bayesian seismicity models: Introduction to a program package

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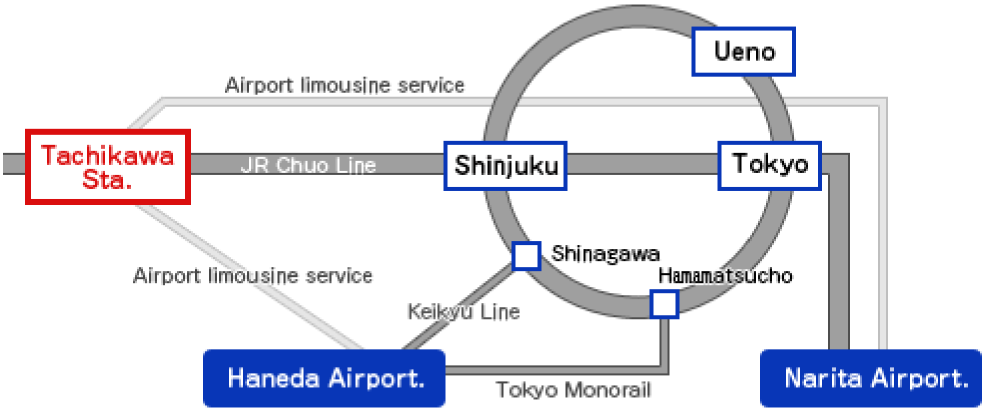
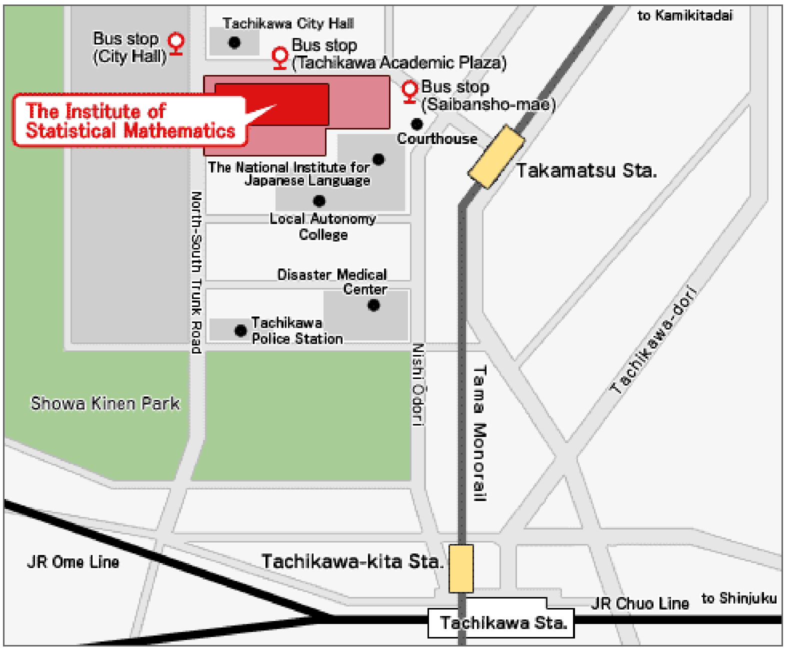
We are very soon publishing a set of programs with their manuals for estimating Bayesian point process models of seismic activity. The Bayesian models include nom-homogeneous spatial Poisson processes, location-dependent b-values of Gutenberg-Richter law, and location-dependent space-time ETAS models. Since seismic activity is highly clustered in space, we adopt Delaunay-based parameterization for the coefficients of spatial functions rather than differentiable smooth spline functions or kernel functions. In this talk, I would like to introduce the computational procedures for these estimations with some illustrative examples.





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