HIST-ETAS models - revisited with emphasis on background seismicity

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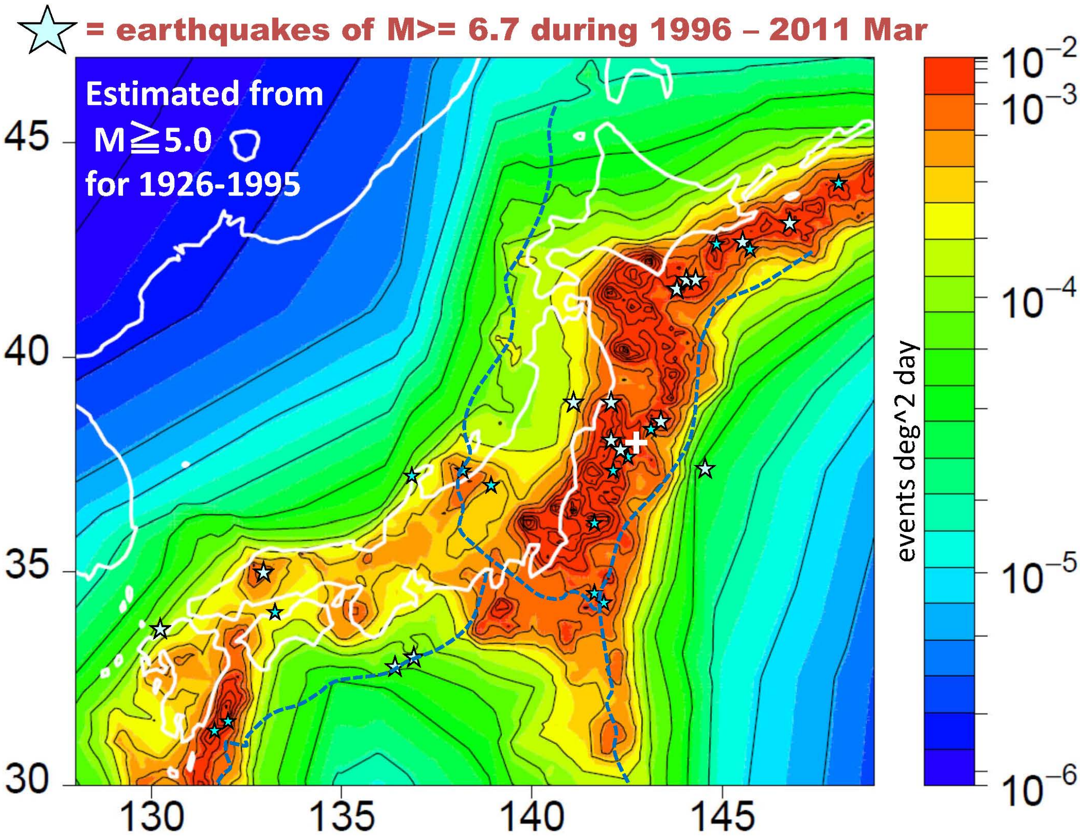
It has been passed about 15 years since the hierarchical space-time ETAS (HIST-ETAS) models have been proposed; and the short- and intermediate-term earthquake forecasts in and around Japan using the HIST-ETAS model is under examining for 8 years by the Testing Center of the Collaborative Study of Earthquake Predictability (CSEP).

Some parameters of the HIST-ETAS model are characterized by a two dimensional piecewise linear function whose value at any location is linearly interpolated by the values at the nearest three earthquake locations that consists a Delaunay triangle. The solutions of the parameter functions are obtained through the inversion of the log-likelihood function of the space-time earthquake data, with certain smoothness constraints. This is suited not only for high resolution inversion in the region of clustering of earthquakes but also accurate space-time forecast in the active stage of seismicity.

Among the parameters of the HIST-ETAS models, we are primary interested in that of the background seismicity. This values can regionally vary in the range of several orders is in a seismogenic zone, but the solutions are confirmed to be independent of observed periods. Hence this is quite useful for the secular prediction of large earthquake locations, in conjunction with Gutenberg-Richter distribution where the b-value is also location dependent.

In this talk, I will show examples of such forecast in Japan inland and vicinity, California, and the global seismicity. The relevant software codes and manual can be obtained by the request mail to ogata@ism.ac.jp.

Keywords: space-time ETAS model, Delaunay triangulation, background seismicity


= earthquakes of M>= 6.7 during 1996 – 2011 Mar
Estimated from
M≧5.0
for 1926-1995
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events deg^2 day

Empirical forecast of occurrence of mainshocks based on foreshock activities
- Applied to the specific five regions and inland area of Japan -

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1. Introduction

Generally it is quite difficult to distinguish foreshocks from background seismicity before a mainshock occurs. However, it is known that some activities like swarms tend to be followed by large earthquakes. We have investigated statistical features of swarm-like activity and searched for the best parameters to define foreshocks. So far, we have reported that such defined foreshock activities are particularly effective for specific three regions in Japan: along the Japan trench, off the Izu peninsula region, and in the north-central Nagano prefecture. In this study we report the current status of prediction performance for these three regions basing on the latest data and also the results for newly investigated regions: the central part of Kyushu and the San-in districts. Besides, we also demonstrate the preliminary results of prediction performance for the inland area of Japan using the temporally applied parameters.

2. Method

The method to search for parameters for foreshocks that present high prediction performance consists of four steps. 1) To eliminate small aftershocks from the original data. 2) To define foreshock candidates satisfying the condition that earthquakes of count Nf with magnitude >= Mf_0 occur in the segment of the size of D x D degree (latitude x longitude) during the period of Tf days. 3) To set the alarm period of Ta days during which a mainshock is expected to occur after a foreshock candidate is found. 4) To search for the values of D, Mf_0, Tf, Nf and Ta which give high prediction performance for mainshocks with M >= Mm_0 by the grid search method. The prediction performance is measured mainly by dAIC that is defined as the difference of AIC for a stationary Poisson model and a foreshock-based model mentioned above, and additionally by alarm rate (AR: the fraction of mainshocks alarmed), truth rate (TR: the fraction of foreshock candidates followed by a mainshock), and probability gain (PG: the ratio of mainshock occurrence rate in the predicted space-time to background occurrence rate).

3. Data and Results

1) Along the Japan Trench

We applied the above method to the earthquakes in three regions along the Japan trench, i.e., off Iwate, off Miyagi and off Ibaraki, cataloged by JMA. The prediction performance for the latest period from 1961 to 1/31/2017 is expressed as AR=27% (=13/48) and TR=22% (=17/77) for Mm_0=6.0 by applying the best parameters (D=0.5 degree, Mf_0=5.0, Tf=10 days, Nf=3, and Ta=4 days) obtained for the period of 1961-2010.

2) Off the Izu Peninsula

The prediction performance from 1977 to 1/31/2017 resulted in AR=68% (=44/65) and TR=22% (=44/197) for Mm_0=5.0 by applying the best parameters (D=0.2 degree, Mf_0=3.0, Tf=3 days, Nf=3, and Ta=5 days) obtained for the period of 1977-6/30/2013.

3) North-central Nagano Prefecture

The prediction performance from 1998 to 1/31/2017 resulted in AR=45% (=5/11) and TR=11% (=8/70) for Mm_0=5.0 by applying the best parameters (D=0.1 degree, Mf_0=2.0, Tf=1 day, Nf=5, and Ta=5 days) obtained for the period of 1998-2014.

4) Central Kyushu District
The prediction performance from 1970 to 1/31/2017 resulted in AR=31% (=4/13) and TR=6.5% (=3/46) for Mm_0=5.0 by applying the best parameters (D=0.1 degree, Mf_0=3.0, Tf=10 days, Nf=3, and Ta=12 days) obtained for the period of 1977-3/31/2016.

5) San-in District
The prediction performance from 1977 to 1/31/2017 resulted in AR=24% (=5/21) and TR=11% (=4/37) for Mm_0=5.0 by applying the best parameters (D=0.1 degree, Mf_0=3.0, Tf=1 day, Nf=2, and Ta=24 days) obtained for the period of 1977-12/31/2016.

6) Inland of Japan
The prediction performance from 1977 to 1/31/2017 resulted in AR=12% (=23/190) and TR=4.6% (=30/657) for Mm_0=5.0 by applying the same parameters for off the Izu peninsula region.

Keywords: earthquake prediction, foreshocks, statistics, performance

Earthquake modeling incorporating non-seismic data

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Although early studies suggested a certain amount of precursory information in both earthquake catalogs and non-catalog observations, the earthquake forecast is still far from satisfactory at present. In most case, the precursory phenomena were studied individually. An earthquake model that combines self-exciting and mutually exciting elements was developed by Ogata and Akaike from the Hawkes process. The core idea of this combined model is that the status of the event at present is controlled by the event itself (self-exciting) and all the external factors (mutually exciting) in the past. In essence, the conditional intensity function is a time-varying point process, which is composed of the background rate term, the self-exciting term (the information from past seismic events), and the external excitation term (the information from past non-seismic observations). This model shows us a way to integrate the catalog-based forecast and non-catalog-based forecast. Meanwhile, measurements of electromagnetic fields and GPS ground deformations have documented accumulative signals associated with large earthquakes during the past few decades. To date, a large number of statistical investigations have shown the correlation between these signals and large earthquakes. As an attempt, we are trying to develop new earthquake models which incorporate information from both earthquake catalog and non-seismic observations.

Keywords: Earthquake modeling, the self-exciting and mutually exciting model, GPS ground deformation, geo-electromagnetic variations

A Mechanism Causing the Temporal Variation in b-values Prior to a Mainshock

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Observations exhibit the temporal variation in b-values prior to a mainshock. The b-value starts to increase from the normal value at time t_1, reaches its peak one at time t_2, then begins to decrease from the peak one at t_2, and returns to the normal one at time t_3. As $t>t_3$, the b-value varies around the normal one or rightly decreases with time until the occurrence of the forthcoming mainshock at time t_4. The precursor time, $T=t_4-t_1$, of b-value anomalies prior to a forthcoming mainshock is related to the magnitude, M, of the event in a form: log(T)=q+rM (T usually in days) where q and r are two constants. In this study, the mechanism causing b-value anomalies prior to a mainshock is explored. From numerical simulations based on the 1-D dynamical spring-slider mode proposed by Burridge and Knopoff (1967), Wang (1995) found a power-law correlation between b and s, where the parameter s is the ratio of the spring constant (K) between two sliders to that (L) between a slider and the moving plate. The power-law correlation are $b\tilde{}s^{-2/3}$ for the cumulative frequency and $b\tilde{}s^{-1/2}$ for the discrete frequency. Since L of a source area is almost constant for a long time period, b directly relates to K. Lower K results in a higher b-value. Wang (2012) found $K=\rho_A v_p^2$, where ρ_A and v_p are, respectively, the areal density and P-wave velocity of a fault zone. Experimental results show that v_p is strongly influenced by the water saturation in rocks. The water saturation in the source area varies with time, thus leading to a temporal variation in v_p as well as K. This results in the temporal variation in b-values prior to a mainshock. The modeled result is consistent with the observation.

Keywords: earthquake precursor, b-value, precursor time, earthquake magnitude, water saturation, spring-slider model

On high-frequency energy release by aftershocks of several inland large earthquakes in Japan

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Detection of aftershocks occurring immediately after a large earthquake is generally difficult because their waveforms overlap in seismograms. Therefore, it takes usually more than one day before a reliable aftershock forecasting becomes available from a conventional catalog-based method. This method is often too late for the largest aftershock that tends to occur within one day after the mainshock. To overcome this defect, in this study, we propose another approach that detects high-frequency energy release by all the aftershocks occurring from immediately after the mainshock. In this approach, instead of detecting the aftershocks one by one, we estimate a continuous energy release by the aftershocks. By applying an inversion scheme to envelope of continuous seismograms of Hi-net, we estimate spatiotemporal distribution of energy release by the aftershocks. For saturated Hi-net records, we alternatively use KiK-net records that co-located with the Hi-net sensor, which enables us to use data of wide dynamic range from microseisms to strong ground motion. In theory, the estimated energy release is not disturbed by “missing” of the event detection. So far we apply this inversion scheme to 8 inland large earthquakes occurred in Japan, where their M_J ranges from 6.3 to 7.4. The target frequency range of the seismogram is from 4 to 20 Hz.

The estimated cumulative energy normalized by their mainshock energy distributes from 0.017 to 1.37. This normalized cumulative energy (NCE) does not show clear dependence on the mainshock energy. NCE represents relative productivity of aftershocks: the aftershock activity is closer to “swarm” type rather than “mainshock-aftershock” type when NCE is larger. Among the analyzed 8 events, the 2004 Chuetsu earthquake is the only case whose NCE exceeds 1, which means the energy released by its aftershocks exceeds the energy released by the mainshock. As expected from the Omori-Utsu law, amount of energy release is larger at earlier lapse times. By the first 1 hour after the mainshock, 9 % to 73 % of the aftershock energy released within 7 days is released. This percentage becomes 10 % to 79 % and 28 % to 96 % by the lapse times of the first 3 hours and 6 hours, respectively. For 5 of the 8 analyzed events, more than half of the 7 days’ aftershock energy is released within the first 6 hours. This result strongly suggests that using energy release by aftershocks within the first several hours is essential to improve the method of aftershock forecasting.

Keywords: aftershocks, high-frequency energy release, Hi-net, realtime aftershock forecasting

An extensive study of clustering features of seismicity in Italy during 2005 to 2016

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Compiled by INGV, the ISIDE catalog includes high quality records of the occurrence times, locations, and magnitude of earthquakes that occurred in the Italy region since 2005-4-16. To study the characteristics of seismicity in Italy, we use the space-time ETAS model and several extended forms. Our results show: Seismicity clustering features are quite different from region to region. According to the ETAS parameters, the whole study region can be divided into four subregions.
The rupture geometries of large earthquakes, including the 2009-4-6 M6.3 L'Aquila, the 2012-5-20 M6.1 Emilia, the 2016-0-24 M6.0 Amatrice, the 2016-10-30 M6.2 Norcia earthquakes, control the spatial locations of their direct aftershocks. These direct aftershock aftershock mainly concentrate near, some parts close to the parts on the rupture plane with large slips but seldom overlap with them, indicating that aftershocks are the continuation of the rupture process of the mainshocks.
When the focal depth is considered in seismicity modeling, improved probability forecasting of seismicity and hazard assessment can be obtained.

Keywords: Earthquakes in Italy , space-time modelling

Bridging Geodesy and Seismology to study fault slip behavior in space and time

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Finite rupture models of past large earthquakes provide insights to rupture physics and the gained information feeds into rupture simulations and simulated ground-motion. An obstacle are the commonly high uncertainties corresponding to hazard-relevant rupture characteristics like precise fault location, rupture dimension, slip or moment rate and rupture velocity. More robust inferences of rupture models with reduced uncertainties can be achieved through a combination of near-field and far-field data such as strong-motion, GPS and InSAR surface displacement data and broadband teleseismic data, respectively. Because GPS and strong-motion observations depend on dense local instrument networks, a global coverage of onshore crustal earthquakes is realized only by combining space-borne InSAR data and broadband seismic waveform observations.

Additionally, InSAR time series data can be used to measure interseismic fault loading and stress-releasing aseismic fault slip, like fault creep or postseismic afterslip. Taken together these observations reveal slip deficits and earthquake potential at fault systems. The consideration of the latter is important in strain-based earthquake forecasts.

We present our ongoing work in the German young researcher group project “Bridging Geodesy and Seismology” (www.bridges.uni-kiel.de) to facilitate the combined use of InSAR data and seismic waveforms to model seismic finite rupture processes in a harmonized modeling framework. To do so we extend the existing open-source seismology community toolbox pyrocko (www.pyrocko.org) by modules that allow for the additional use of near-field static offsets in combination with far-field seismic waveforms for finite rupture modeling.

The relationship between fault slip at depth and surface displacement is highly non-linear and the fault continuation at depth is not precisely known. As a consequence, best-fit model solutions are often highly ambiguous. For studying the coseismic slip, fault afterslip, creep and/or interseismic fault loading we therefore need to explore a large model parameter space and estimate model parameter trade-offs, e.g. between fault geometry at depth and slip potential, and uncertainties of model parameters. To do so as realistically as possible we use Bayesian modeling approaches which includes the propagation of correlated data error. We are working on also propagating the medium model uncertainties that have been shown to significantly bias the estimation of rupture parameters.

Our goal is to facilitate combined-data finite rupture modeling for more robust earthquake source estimations, to find best-practice modeling standards and to provide examples for enriched earthquake catalog data of finite sources with their model probabilities. We want to use these to better understand the resolution limits on earthquake source characteristics from surface data and possibly strengthen source scaling relations. Furthermore, we are interested in the properties of aseismic slip and loading to

improve the knowledge the seismic potential.

This research is supported by the German Research Foundation DFG.

Keywords: earthquake source, earthquake source modeling, InSAR, seismic cycle, earthquake hazard, rupture modeling

Beyond Omori: Continuous mapping of energy release during the Kaikoura Mw7.8 earthquake sequence

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The Omori Law, has greatly influenced the field of seismology since its publication in 1894. The law describes the fundamental nature of earthquakes as patterns of a large earthquakes followed by aftershocks. The modified-Omori Law remains a cornerstone of modern seismology more than 100 years after its discovery. This law is based on the assumption that aftershock generation processes are represented by traditional catalogues of earthquake magnitudes and locations. There are many reasons to believe this fundamental assumption is wrong. We have begun to delve deeper into the understanding of these earthquake processes by looking beyond catalogues. We quantity basic physical measurements that directly relate ground motions recorded by seismometers on the Earth surface to energy released within the earth. By quantifying this energy release through time and space, we are attempting to develop a more accurate view of the seismological process by circumventing problems associated with standard earthquake catalogues.

Omori decay has been shown to vary significantly between earthquake sequences. Often, the modified-Omori Law is combined with the Gutenberg-Richter Relation to describe not just the decay in numbers of earthquakes, but also the distribution of earthquake magnitudes. It is our controversial contention that the use of traditional earthquake catalogues to define these relations is inadequate because of three main shortcomings. 1) Quantifying the huge number of discrete earthquakes in the seconds and minutes following a big earthquake is at least difficult, and perhaps impossible. 2) The different magnitude scales used to quantify earthquake are inconsistent. For example, Richter magnitude calculation works well for small earthquakes, but not large ones; Moment magnitude calculation works well for large earthquakes but not small ones. Unfortunately, Richter magnitude and moment magnitude measure different quantities. 3) Traditional earthquake catalogues do not do not detect many newly discovered ‘slow earthquakes’. Many of these slow earthquakes release seismic energy, but that energy is also not captured by traditional magnitude measures. We attempt to overcome these limitations by quantifying the behaviour of the Earth during an earthquake sequence by looking at the most fundamental measurement of Earth's deformation, the release of energy. To do this, we back project ground motions recorded by seismometers to continuously quantify the amount and location of energy released by the earth. As back projection is a non-unique solution to the energy radiation problem, we impose mapping criteria to minimize the duplicate counting of large energy envelopes.

The recent Kaikoura Mw7.8 earthquake is an ideal earthquake sequence on which to test our idea. It is unique in that it affected both crustal (shallow) and subduction (deep and shallow) faults, triggering widespread aftershocks, tremor, and slow earthquakes. We will present a time-dependent model of energy release throughout this sequence and compare it to models based on the Omori Law and discuss implications of this comparison on triggering and earthquake clusters.

Keywords: earthquake energy, Kaikoura Earthquake, back projection, aftershock, Omori, earthquake statistics

Is the *b* value of foreshocks an effective signature in the prediction of a large earthquake occurrence?

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The Gutenberg-Richter frequency-magnitude distribution of earthquakes is now well established in seismology. The slope of the relation between frequency and magnitude (*b* value) is typically 1, but it often shows variations around 1. Spatial and temporal changes in *b* are thought to reflect stress state in the Earth's crust (Schorlemmer et al., 2004, 2005). In this context, such observations that *b* values of foreshocks (earthquakes that occur immediately before large earthquakes, close to the hypocenters) are lower than the typical $b = 1$ have been considered to indicate that areas near hypocenters of large earthquakes are under high stress. However, it has remained uncertain whether *b* values of foreshocks are significantly low compared to those of stationary seismicity and aftershocks in the area, so as that the *b* value can be used as an indicator of impending large earthquakes.
In order to clarify the above-described issues, we have conducted a systematic investigation into *b* values of foreshocks of large earthquakes in and around the Japanese islands. Here we show preliminary results obtained by the investigation. We used the earthquake catalog of the Japan Meteorological Agency (JMA). The criteria adopted to define a main shock is that a larger earthquake does not occur in the previous y_1 days and within a distance *L*. In addition, a larger earthquake must not occur in the selected area in the following y_2 days. We used $L = 100$ km, $y_1 = 3$ days and $y_2 = 0.5$ days. In our preliminary analysis, mainshocks were chosen from earthquakes with a magnitude (*M*) of 5-6 that occurred in and around the Japanese islands during 1995-2016. Foreshocks are all events occurring in the preceding time interval of $t = 3$ days and within a circle of radius *R* km from the mainshock epicenter. We chose $R = 10$, 30, and 50 km. These *R* values are equivalent to 2, 6, and 10 fault lengths of *M*5-6 class earthuakes, respectively. In choosing these parameter values, we referred Lippiello et al. (2015). Further study will be required to define appropriate parameters.
Schorlemmer et al. (2005) found that normal faulting events have the highest *b* values, thrust events the lowest and strike-slip events intermediate values. We used information on the focal mechanisms from the F-net Broadband Seismograph Network database to classify main shocks as strike-slip, thrust or normal events. We then stacked foreshocks for each of the types of mainshock faulting and computed *b* values of foreshocks corresponding to each of the styles of faulting. We found that *b* value of foreshocks varies systematically according to the rake angle of faulting and the result is consistent with that obtained by Schorlemmer et al. (2005). We plan to conduct a more thorough investigation into the *b* values of foreshocks. We are going to expand our analysis to offshore earthquakes, including the 2011 Tohoku-Oki earthquake (Nanjo et al., 2012; Tormann et al., 2015), before which a very clear decrease in the *b* value to as low as $b = 0.5$ was observed near the hypocenter.

Keywords: the Gutenberg-Richter frequency-magnitude law, faulting, stress

Significant Decrease of Seismicity in the Northeastern Margin of the Japan Sea after the Mega Thrust Event on Mar. 11, 2011

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Since Matsu’ura (1986) first showed the quantitative way to detect relative quiescence in seismicity during aftershock sequences, the relative quiescence of seismicity has been a good index to prognosticate the occurrence of large earthquakes. Ogata (1988) extended it to the wider area with the proposal of ETAS model as the quantitative expression of the ordinary seismicity. Since we have the reliable catalogue of earthquakes of M6.0 and larger in and around Japan for more than 130 years, we could detect the largest relative quiescence lasting for 10 years in the area east off Tohoku district, prior to the M9.0 2011 earthquake off the Pacific coast of Tohoku (Matsu’ura, 2008). Here we report the current significant decrease of seismicity in the northeastern margin of the Japan Sea area.
The 2011 earthquake off the Pacific coast of Tohoku dramatically changed the seismicity in and around Japan, especially in the northeastern Japan. For example, many shallow earthquakes now frequently occur in the north Ibaraki area and Iwaki area, where the seismicity had been very low before the 2011 mega thrust event. The area currently showing the relative quiescence includes the seismic gap between the source areas of M7.7 1983 central part of the Japan Sea earthquake and M7.8 1833 Tenpo off Dewa district earthquake, without any known large event for the recent 400 years (e.g. Matsu’ura et al, 2012).
Since JMA finished the revision of the hypocenter catalogue, which had been delayed after 2011, by the end of March in 2014, we used the JMA catalog for the period from October 1997 to January 2017. To avoid the intentional area or event selections, we firstly analyzed the whole earthquakes of M=2.5 and larger and depth=60km and shallower within the wide area of (37°N, 137°E) –(41.6°N, 140.1°E), where some major activities before 2011 and induced events after 2011 are included. Even though, it is apparent that the seismicity decreased since 2013 in that wide area. If the analyzed area is set narrower around the gap, it becomes clearer. In the figure 4(A) of Ogata (2011) showed the apparent relative quiescence prior to the M7.7 1983 event and M7.8 1993 event in the same region. We cannot conclude now whether the current quiescence represents the same physical status as those prior to 1983 and 1993 cases, or just shows the weakened compressional stress field in the northeastern margin of the Japan Sea due to the 2011 event. However, we should watch the area and search other clue to obtain the answer.

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Keywords: Relative Quiescence of Seismicity, Northeastern Margin of the Japan Sea, Seismic gap off Akita City

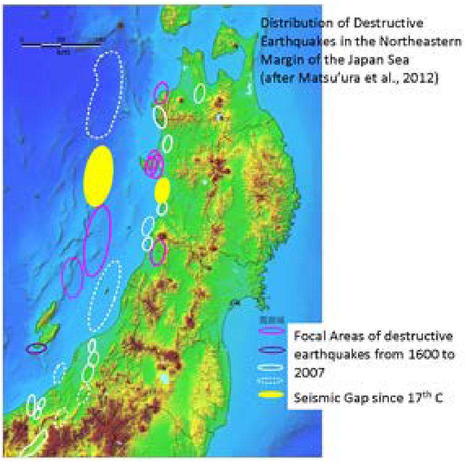

Fig. 1(a) Distribution of focal areas of the recent 400 years in the northeastern margin of the Japan sea and the gaps.

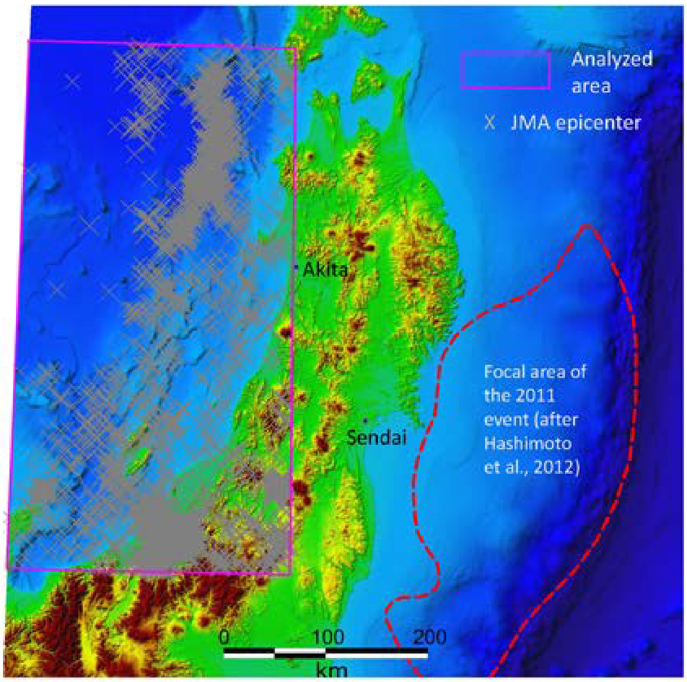

Fig. 1(b) Epicenters of counted events in (c). The focal area of M9.0 event in 2011 is also shown. Earthquakes of M>=2.5 and Depth<=60km in the area are all used in (c).

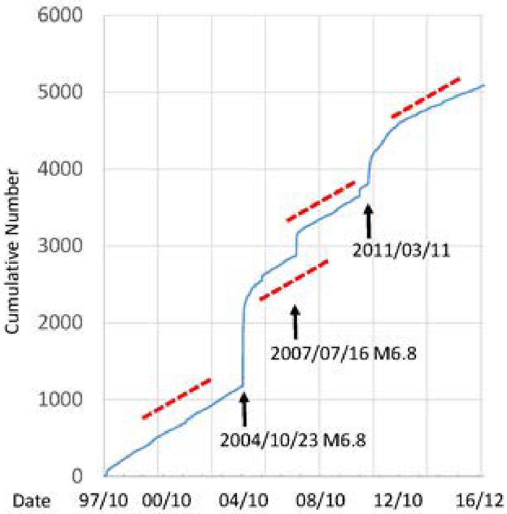

Fig. 1(c) Cumulative number of earthquakes since 1997 Oct. 1st. Times of two large events within the analyzed area shown in (b) and the M9.0 are shown by arrows. All red broken lines show the same occurrence rate.

Earthquake forecast modelling for the Mw 7.8 Kaikoura Earthquake and triggered Slow Slip Events

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1. GNS Science

The November 14th, 2016, *M*w 7.8 Kaikoura, New Zealand earthquake affected a large part of central New Zealand. The event ruptured around 12 independent faults and caused significant damage and shaking in many areas. This has meant that recovery effort has also been distributed over a very large area and has required a new approach to the dissemination of information about the potential for future shaking. We have provided forecasting information that targets a broad range of end-users who have become increasingly sophisticated in their use of the forecast information. Our information has ranged from aftershock probability tables through to detailed and specific engineering information. Additionally, the main shock triggered three slow slip events (SSE) on the Hikurangi subduction zone that were unique in character in our approximately 20 years of observations; these SSE provided a difficult challenge to the on going forecasting efforts and required a new approach to incorporate the effect of the SSE.
As is typical in such aftershock sequences, data quality issues have provided a challenge to the forecast modelling. The models we have applied are based on our past work and have used a hybrid of the STEP, ETAS and EEPAS models to produce the forecasts. An important change has been the use of the negative binomial distribution, constrained by ETAS simulations (Harte, 2013), to describe the uncertainty in the STEP rates. These uncertainties were also used to produce stochastic events sets for use in hazard calculations for engineering decisions (e.g., forecast design spectra as compared to the design standard or probabilities of landslide). To date the aftershock productivity has been low when compared to average New Zealand aftershock behavior.

Keywords: New Zealand, earthquake forecasting, slow slip event

Earthquake forecast based on a magnitude difference between the largest and the second largest earthquakes

*Ken'ichiro Yamashina[1]

1. none

Based on a statistical study on a magnitude difference between the largest and the second largest events in each earthquake sequence, the author proposed a pair of earthquakes with similar magnitudes may be a signal of an impending larger earthquake (e.g., Yamashina, K., J. Phys. Earth, 29, 1981a; Maurice Ewing Ser. 4, 1981b). For example, when a magnitude difference is equal to or less than 0.4 (if the second largest event precedes the larger one) or 0.2 (if vice versa), another larger event will occur with the probability of about 20-30%. In contrast, the probability will become very small when the value of a magnitude difference is large.
Since the proposal, more than 30 years have passed, and many data of earthquake sequences were accumulated. Among them, e.g., the Off-Ibaraki-Prefecture (central Japan) earthquake of M7.0 in 2008 was preceded by events with M6.4 and M6.3 (in JMA scale), and prospectively worried about the occurrence of a larger event with a magnitude around 7.0. The Kumamoto-Prefecture (southern Japan) earthquake of M7.3 in 2016 was also preceded by events with M6.5 and 6.4 (in JMA scale). In case of the L’Aquila (central Italy) earthquake of M6.3 in 2009, the occurrence of events with M4.1 (30 March) and M3.9 (5 April; in INGV scale) might have been useful to warn a possibility of the disastrous main shock (6 April), which occurred several hours after the event with M3.9.
In a typical main-and-aftershock sequence, a magnitude of the largest aftershock is far less than that of a main shock. It will be important that a magnitude difference between the largest two events is a good indicator whether they are considered to be an ordinary main-and-aftershock sequence or not. Although a success rate of the present method of earthquake forecasts is not large, it will still help to prompt an examination of various observed data, and also to call attention to a preparatory check against unexpected disasters. Recently, a detailed statistical analysis for a magnitude difference between the largest two earthquakes is carrying out by Dr. Shunichi Nomura and others. The author appreciates the progress of the present subject.

Keywords: earthquake forecast, magnitude difference, the largest earthquake, the second largest earthquake

