Increased probability of large earthquakes near aftershock regions with relative quiescence

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Abstract. It is shown that after a large earthquake of $M6$ class or over has taken place, another event of similar size or larger is relatively more likely (in the sense of rate per unit area) to occur in the near field than in the far field. In particular, we show that the aftershock activity of the first event provides useful information for assessing the probability of a following large event in the neighborhood (within a distance of a few degrees). Namely, if the aftershock activity from the first event becomes relatively quiet compared to the normal decay, the occurrence rate of larger events in the neighborhood is several times higher during the first decade after the main shock than would be the case for normal aftershock activity. For measuring such phenomena precisely, we need to model the normal aftershock activity. In fact, many aftershock sequences are more complex than the simple inverse power decay represented by the modified Omori formula. The epidemic type aftershock sequences (ETAS) model is a generalized version of the modified Omori formula, which fits well with various aftershock sequences, including nonvolcanic type swarms. Using this model, aftershock sequences are investigated for the 76 main shocks that occurred in and around Japan during the last three quarters of a century. The focus is placed on objective examination of whether or not, in an aftershock sequence, there exists a significant change point followed by relative quiescence, that is, a significant lowering of the seismicity from that predicted by the ETAS model. Relative quiescence can take place regardless of the seismicity level. The extent of such quiescence, if it exists, is seen from the diagrams of cumulative numbers versus the transformed occurrence times based on the predicted occurrence rate by the estimated ETAS model. It is thus demonstrated that relative quiescence can be a helpful factor in detecting anomalous aftershock activity. This can then be used to forecast whether or not a large event is more likely to follow shortly (within $\sim$6 years) in the neighborhood (within a distance of 3°) of the initial event.

1. Introduction

Once a large earthquake has taken place, we usually do not expect another large event of similar size or greater at the same location until a substantially large time span has elapsed. The gap theory and characteristic earthquake theory advocate this view. However, the story changes if the area in focus is the neighborhood of the source region. Statistical analysis of the configuration of epicenters of earthquakes with any threshold magnitude level, no matter how large, show inverse power correlations decaying in distance [*Kagan and Knopoff*, 1980]. Similar correlation is seen in time, even for large events [*Ogata*, 1988; *Ogata and Abe*, 1991]. There are many reports which have described the migration of earthquakes [e.g., *Mogi*, 1968a]. *Oike* [1980] lists 12 pairs of large earthquakes which occurred subsequently in the same neighborhood of Japan. Recent intensive study into the triggering of earthquakes by the sudden change of a stress field around the source may support these observations [see, e.g., *Harris*, 1998]. Therefore it will be interesting to investigate the seismic activity which would reflect the state of the stress field around a region prior to the next large event.

On the other hand, prior to a major earthquake, seismic quiescence, gap, and foreshocks are expected to emerge over a wide region including the focal region. Since the pioneering works by *Inouye* [1965], *Utsu* [1968], *Mogi* [1968b, 1969], and *Ohtake* [1980], statistical methods have been proposed for the quantitative description of quiescence aiming at earthquake prediction [e.g., *Reasenberg and Matthews*, 1988; *Wyss and Habermann*, 1988; *Matthews and Reasenberg*, 1988; *Ogata*, 1988, 1989, 1992] based on the background seismicity in narrow to wide regions.

In this paper, in view of the above statement, we study the local seismic activity, namely, aftershock sequences including swarms of the second kind [*Utsu*, 1970]. This is because the seismicity in a narrow region is likely to be homogeneous in space, which makes our statistical analysis feasible for a data set of many events. However, conventional methods based on a declustering catalog are not applicable for the present analysis because aftershocks themselves are clusters. Thus we need modeling of the clustered feature to detect and measure anomalies of the activity. In particular, the anomaly in focus is the relative quiescence [*Ogata*, 1985, 1988, 1992], which is defined as a rate of earthquake activity that is significantly lower than the predicted occurrence rate for standard seismic activity. Notably, *Matsu'ura* [1986] studied aftershock sequences extensively in Japan and its vicinity to reveal the relative quiescences preceding conspicuously large aftershocks, which triggered secondary aftershocks [*Utsu*, 1971] by using the statistical methods established by *Ogata* [1983a, 1983b, 1985] and *Ogata and Shimazaki* [1984]. Matsu'ura applied nonstationary Poisson processes with the modified Omori intensity function, concentrating on the quiescence for a short time span, say, a few days long, prior to conspicuously large aftershocks (see also *Zhao et al.* [1989] for similar analysis of Chinese aftershocks).

In this paper we focus on the examination of relative quiescence for a longer time span, say, for several months to several years, in an aftershock sequence or swarm in order to investigate the statistical relation to another large event near the source region. Consequently, the aftershock activity becomes more complicated than the Poisson process as the time span gets larger, which requires the extension of the simple modified Omori decay. Section 2 describes the epidemic type aftershock sequence (ETAS) model. When the Poisson process with modified Omori intensity is applied to the aftershocks, only the occurrence time data are used. However, as seen in the ETAS model, the associated magnitude data can also be used for analyzing more complex activities. We primarily use the hypocenter data of the Japan Meteorological Agency (JMA) for the period from 1926 up to the present, occasionally combining this with time series of felt/unfelt shocks recorded by certain JMA observatories.

2. ETAS Model for Aftershocks

Aftershock statistics has been a unique research subject in Japan since the pioneering work by *Omori* [1894]. Especially, *Utsu and Seki* [1955], *Utsu* [1957, 1961, 1962, 1969, 1970, 1971, 1972], and *Mogi* [1967] extensively investigated various aspects of aftershock statistics. In particular, the modified Omori formula [*Utsu*, 1957, 1961]

$$\lambda_\theta(t) = \frac{K}{(t+c)^p}, \quad \theta = (K, c, p), \tag{1}$$

where λ_θ is the rate of aftershock occurrence and t is the time elapsed from the main shock, is important for measuring the decaying activity of aftershocks. After a major earthquake its p value has been reported in the aftershock studies including those by the JMA. In many cases, however, aftershock sequences become more complex than the simple modified Omori formula, as schematically shown in Figure 1. *Utsu* [1970] extensively studied such activity including the secondary aftershocks. In a quantitative study, *Ogata* [1983a, 1985, 1988, 1989] suggested the epidemic type aftershock sequences (ETAS) model for identification of aftershock activity in a source region and also for the standard general seismicity in a fairly wide area.

Figure 1

Consider the occurrence data $\{(t_i, M_i); i = 1, \cdots, N\}$ of earthquakes with threshold magnitude M_c such that $M_i \geq M_c$ on an observed time interval $[0, T]$ where the main shock occurred at the time origin 0. Then the ETAS model is defined as follows. Let a constant parameter μ stand for the background seismicity of the region and assume that every event (t_i, M_i) triggers its own aftershocks with the intensity following the modified Omori formula:

$$\nu_i(t) = \frac{K}{(t - t_i + c)^p}\, e^{\alpha(M_i - M_0)}, \tag{2}$$

where the parameters K, α, c, and p are common to all i and M_0 represents the magnitude of the main shock throughout this paper. Thus the occurrence rate of earthquakes in a region is given by the superposition of $\nu_i(t)$ in (2) such that

$$\lambda_\theta(t|H_t) = \mu + \sum_{\{i:\ t_i<t\}} \nu_i(t), \tag{3}$$

where H_t represents the history of events $\{(t_i, M_i);\ t_i < t\}$ up to time t. In many cases we can assume $\mu = 0$ for carefully extracted aftershock sequences from a catalog. For the case where the selected sequence may include other events than aftershocks especially when (or where) location accuracy is not good, we can assume $\mu > 0$ to compare the goodness of fit to the data with $\mu = 0$ by using the Akaike information criterion (see section 3).

Among the above five parameters characterizing the ETAS model the three parameters K, p, and α are useful for characterizing an aftershock sequence. The α value measures an efficiency of magnitude difference of an earthquake in generating its offspring, or aftershocks. For instance, swarms have small α values usually < 1, while aftershock activity without conspicuous secondary aftershocks in the sequence has large α values so that $\nu_i(t) \approx 0$ for all $i \geq 1$. The p value indicates the decaying rate of triggered effect in lapse time, and K measures the level of aftershock activity relative to the size of the main shock.

3. Estimation, Model Selection, and Residual Analysis

Suppose that the main shock took place at the time origin $t = 0$ and that the occurrence data are $\{(t_i, M_i);\ 0 \leq t_i < T\}$. Since smaller events are hard to detect for some time span immediately after the main shock, we set an appropriate time S after which the aftershock events with $M_i \geq M_c$ are homogeneously detected. Then we use the maximum likelihood estimates (MLE) which maximize the log-likelihood function

$$\ln L(\theta; S, T) = \sum_{S<t_i<T} \ln \lambda_\theta(t_i|H_{t_i}) - \int_S^T \lambda_\theta(t|H_t)dt, \tag{4}$$

where ln is natural logarithm. Here it is noted that although only the data for the span $[S, T]$ are fitted, data in $[0, S]$ including the main shock are used for calculation of the log-likelihood function in (4): remember that the ETAS model $\lambda_\theta(t|H_t)$ in (3) is a function of the history from the time origin 0. Regardless of missing smaller events in the span $[0, S]$, large events including the main shock are usually overwhelmingly effective in determining the intensity rate of the future. For more details, see *Ogata* [1988, 1992], *Ogata et al.* [1993], *Guo and Ogata* [1996]. Also see *Utsu and Ogata* [1997] for PC programs for the calculation of the MLE and related statistics with useful manuals.

The Akaike information criterion (AIC) [*Akaike*, 1974]

$$\begin{aligned} \mathrm{AIC} &= (-2)\max\{\text{log-likelihood}\} \\ &\qquad + 2\{\text{number of parameters}\} \end{aligned}$$

is useful to compare the goodness of fit of the models to a given data set, and the model with a smaller AIC value shows a better fit. For example, *Guo and Ogata* [1997] compared the goodness of fit between the modified Omori formula (three parameters) and the ETAS model (four parameters) applied to 34 aftershock sequences of the latest 20 years in Japan and its vicinity. The results were that for two thirds of the sequences the ETAS model was a better fit than the modified Omori formula. In such case the p value of the modified Omori formula is usually smaller than the corresponding p of the ETAS model. For the remaining one third of the sequences where the modified Omori model is a slightly better fit than the ETAS, its p value almost coincided with that of the ETAS. This demonstrates that ETAS is a natural extension of the modified Omori model for studying various types of aftershock sequences.

Suppose that origin time data $\{t_i\}$ are simulated by a predictive occurrence rate function $\lambda_\theta(t|H_t)$ (see *Ogata* [1981] for a simulation method of point processes by thinning). Then consider the integral of the rate function

$$\Lambda(t) = \int_S^t \lambda_\theta(s|H_s)ds, \tag{5}$$

which is then a monotonically increasing function representing the expected number of events in the time interval $[S, t]$. For example, if the modified Omori formula in (1) is assumed for the rate function $\lambda_\theta(t)$, then

$$\Lambda(t) = \begin{cases} K[\ (t+c)^{1-p} - (S+c)^{1-p}\ ]/(1-p) & p \neq 1 \\ K[\ \ln(t+c) - \ln(S+c)\ ] & p = 1. \end{cases}$$

If we consider the time change $\tau = \Lambda(t)$ from t to τ, then $\{t_i\}$ is transformed one-to-one into $\{\tau_i\}$. It is well known that $\{\tau_i\}$ distributes according to the stationary Poisson process with the unit rate. Therefore, if the estimated intensity $\lambda_\theta(t)$ is a good approximation to the true $\lambda(t)$, then the transformed data $\{\tau_i\}$ from the real data are expected to behave like the stationary Poisson process. Namely, $\{\tau_i\}$ are uniformly distributed on the interval $[\Lambda(S), \Lambda(T)]$ given a total number of events.

Since we do not know the true model nor its parameter value, we usually use the model with the MLE $\hat{\theta}$. Then the transformed data of the occurrence times are called a residual point process (RPP). If the model provides a good fit to the seismicity, then the RPP is well approximated by the standard stationary Poisson process. To the contrary, if we find a significant deviation of any characteristic property of the residual point process $\{\tau_i\}$ from that expected under the stationary Poisson, this suggests to us some discrepancy between the model and data, such as heterogeneity of the data or the existence of seismic quiescence which is not included in the model.

For example, Figure 2 shows the aftershock activity of the 1995 Hyogo-Ken-Nanbu (Kobe) earthquake of $M_J 7.2$ and the analysis results using the ETAS model. The occurrence data ranges for 773 days since the main shock and the events with $M \geq 3.0$ are considered. For this data set the ETAS model is slightly better fitted than the simple modified Omori model in (1) as shown by the AIC difference of 2.0. Also, the cumulative curve of the residual process of the ETAS model shown in the transformed time (Figure 2b) demonstrates the excellent fit. The residuals of the simple modified Omori model, although not shown here, are almost the same as that of the ETAS. Figure 2

On the other hand, the aftershock activity ($M \geq 2.7$) of the 1997 Kagoshima-Ken-Hokuseibu earthquake of $M_J 6.5$ shows more complex features. The time span considered is up until the time $T = 47.88$ days when another large event of $M_J 6.3$ ruptured in parallel to the fault of the first event in the southern neighborhood. For this data set the ETAS model is much better fitted than the modified Omori model by the AIC difference of 128.0. Nevertheless, if we fit the modified Omori model to the data set, we can clearly see a number of clusters triggered by large aftershock events as indicated in Figures 3a and 3b.

Figures 3a and 3b

Therefore we fit the ETAS model to the whole period to display the predicted cumulative curves in both the ordinary linear and the transformed timescales (Figures 4a and 4b, respectively). Nevertheless, the cumulative curve of the RPP in Figure 4b shows that goodness of fit throughout the whole period still appears to be poor.

Figures 4a and 4b

Here we hypothesize that the aftershock activity has changed at some time in the analyzed period. For example, Figures 4c and 4d are obtained by assuming that the aftershock activity has changed at 5.23 days after the main shock occurrence. If this is correct, the fit in the first subinterval appears to be good, but the extrapolation of the cumulative curve shows that the events in the second period are substantially fewer than expected. The principal reason for this, seen from the comparison of the predicted and real cumulative curves, would be that the secondary aftershocks triggered by the large aftershocks are not frequent enough in relation to their magnitudes. Therefore it becomes important to judge whether or not the two-stage ETAS model under the above hypothesis fits better than the single ETAS model for unchanging case, For this we need the following change point analysis.

Figures 4c and 4d

4. Change Point Analysis by AIC

In order to examine whether or not the temporal aftershock activity changed before and after a suspected time t in a given data set on a time interval $[S, T]$, we first consider a two-stage model applied to the occurrence data sets on the separated subintervals $[S, t]$ and $[t, T]$, respectively. In addition, the single ETAS model applied to the whole data on the interval $[S, T]$ is considered. Then we calculate the corresponding AICs:

$$
\begin{aligned}
\mathrm{AIC}_0 &= (-2)\max_{\theta}\{\ln L(\theta; S, T)\} + 2k_0, \\
\mathrm{AIC}_1(t) &= (-2)\max_{\theta}\{\ln L(\theta; S, t)\} + 2k_1, \\
\mathrm{AIC}_2(t) &= (-2)\max_{\theta}\{\ln L(\theta; t, T)\} + 2k_2;
\end{aligned}
$$

respectively, where log-likelihoods $\ln L(\theta; \cdot, \cdot)$ are those defined in (4). Further, k_0, k_1, and k_2 are added to account for the number of free parameters utilized in corresponding models to minimize the log-likelihood function. When all the parameters of the ETAS are used, we have $k = 5$. However, in many cases, $k = 4$, for example, when $\mu = 0$ is assumed. In particular, when the number of aftershocks in the latter time span $[t, T]$ is extremely small, we may apply the stationary Poisson process, so that $k_2 = 1$. It should also be noted that $\ln L(\theta; t, T)$ includes the data not only in the time span $[t, T]$ but also in the former time span $[0, t]$ when the ETAS model is applied there, as noted in section 3.

If the change point t is determined based on information other than the data themselves, such as a scientific reason or a systematic setting in advance, AIC_0 of the single ETAS model for the unchanged seismicity is compared with

$$\mathrm{AIC}_{12}(t) = \mathrm{AIC}_1(t) + \mathrm{AIC}_2(t) \tag{6}$$

of the two-stage model for the changed seismicity at the time t. Thus the model with a smaller AIC value is selected. On the other hand, if the change point t is determined somehow on the basis of the data, the above comparison leads to a biased selection in favor of the changed seismicity model even for the data of the unchanged case. This is similar to the issue of how to determine the significance of the maximum of certain statistics in searching the boundary of the changing seismicity [*Matthews and*

Reasenberg, 1987]. To avoid such a bias, the same AIC_0 has to be compared with

$$\mathrm{AIC}_{12}(t) + 2k(N),$$

where the quantity $k(N)$ is the bias correction for searching t to minimize $\mathrm{AIC}_{12}(t)$. The quantity $k(N)$, obtained through simulation experiments [*Ogata*, 1992], is dependent on the number of events N in the interval $[S, T]$ and accurately represented by the Padé approximant

$$k(N) = 1 + \frac{7.6623\, n + 1.9688\, n^2 + 0.022822\, n^3}{1 + 5.0900\, n + 0.95595\, n^2 + 0.0090963\, n^3}$$

for $10 \leq N \leq 2000$, where $n = N/10$.

In the analysis of this paper we will calculate the following statistics

$$\xi(t) = \frac{\mathrm{AIC}_0 - \mathrm{AIC}_{12}(t)}{2} \tag{7}$$

for all times t in $[S, T]$ including all suspected change points. If $\xi(t) < k(N)$ for all t in $[S, T]$, this lead to no significant change point according to the AIC comparison stated above. In any case, $t = T_c$ that takes the largest $\xi(t)$ values over all intervals is considered to be the most suspicious candidate of the change point. When the candidate of the change point T_c is found to be significant (i.e., $\xi(T_c) > k(N)$, or $\mathrm{AIC}_0 > \mathrm{AIC}_{12}(T_c)$), then we confirm that no further significant change points exist in the former span $[S, T_c]$ before examining whether the activity is relatively quiet or activated in $[T_c, T]$.

In order to search the change point, we hereinafter scan the value of $\{\xi(t),\ S < t < T\}$ for a sufficient number of candidates for the change point as compared to the number of events throughout the considered time span $[S, T]$. Since our main interest is the case of small number of events relative to the length of the latter interval, the candidates for possible change points to calculate $\xi(t)$ are taken from all $t = t_i^+$, where t_i^+ means the time immediately after the ith event's occurrence time. We then plot time series of $\{\xi(t_i^+),\ S < t_i^+ < T\}$.

In the case where events in the latter time span $[T_c, T]$ do not seem to be clustered, we may consider the stationary Poisson process for a better model than the ETAS. In particular, when there is no event, $\mathrm{AIC}_2 = 0$ owing to $k_2 = 0$. In any case, both the ETAS and stationary Poisson process models are applied to events in the latter interval in order to take the model with the smaller AIC value, or larger $\xi(t)$ value.

For an illustration of the procedure explained in this section, we reconsider the examples of the two aftershock sequences. The first one is aftershock events with $M \geq 3.0$ for the time span of 773 days of the 1995 Hyogo-Ken-Nanbu (Kobe) earthquake of $M_J 7.2$. Figure 2 shows cumulative number and magnitude versus time plot in the case of linear time (Figure 2a) and transformed time (Figure 2b). There are $N = 541$ events in this time span, and then $k(N) = 3.16$, which is shown by the horizontal dotted line. In view of the missing events with $M \geq 3.0$ for a period immediately after the main shock, we set $S = 0.02$ day: this is written as $t_1 = 0.02$ at the top of Figure 2a for which the vertical dotted lines are indicated, although it is hard to see in Figure 2a. The statistics $\{\xi(t)\}$ are connected by the dashed real lines. All the values $\{\xi(t)\}$ are shown to be below the level of $k(N) = 3.16$, which indicates that no significant change point exists. The same $\{\xi(\tau)\}$ valued for the transformed time τ is also shown in Figure 2b.

The second example is aftershocks ($M \geq 2.7$) of the 1997 Kagoshima-Ken-Hokuseibu earthquake of $M_J 6.5$ that occurred in Kagoshima Prefecture, southern Kyushu Island. Figures 5a and 5b show cumulative numbers and magnitude against ordinary time and transformed time, respectively. The time span considered is $T = 47.88$ days where another large event of $M_J 6.3$ ruptured in parallel to the fault of the first event in the southern neighborhood. In view of the missing events with $M \geq 2.7$, $S = 0.03$ day (which is denoted by $t_1 = 0.03$ in the top margin of Figure 5) is taken, where the vertical dotted line in the beginning is shown but only seen in Figure 5b. The ETAS model is applied to the series of 521 events in the time span $[S, T]$, where $k(N) = 3.15$ is indicated by the horizontal dotted line in Figure5b. Some values of statistics $\xi(t)$ are over the

Figures 5a and 5

level, and the maximum is attained at $t_0 = 5.39$ days indicated by the other vertical dotted lines at which we suspect the change point is significant. Moreover, we examine whether the aftershock sequence in $[S, t_0]$ includes another significant change point. The dashed real line for $\xi(t)$ in Figure 2b shows $\xi(\tau) < k(N)$, where $N = N([S, t_0])$, indicating that no further change points exist there.

5. Relative Quiescence and Relative Activation

Let T_0 be a change point in the interval $[S, T]$ and also suppose that no significant change point exists in the first subinterval $[S, T_0]$. The seismicity in the latter interval $[T_0, T]$ is said to be relatively quiet or relatively activated if the number of events $N([T_0, T])$ in the second subinterval is smaller or larger than the expected number $\int_{T_0}^{T} \lambda_{\hat{\theta}}(t|H_t)dt$, respectively, where MLE $\hat{\theta}$ is obtained by fitting the model to the events of the first subinterval $[S, T_0]$. The relative quiescence is clearly seen by the cumulative number curve of the extrapolated RPP events which is constructed from the estimated model of aftershocks in the first subinterval (see Figure 5b, for example).

In the analysis hereinafter we first examine the existence of a change point, then confirm that no further change point exists in the first subinterval, and finally classify the aftershock sequence into either that of relative quiescence or activation in cases where a change point is found to exist.

Here we note that different models can imply the opposite results of relative quiescence versus relative activation. Recall Figure 3, where the modified Omori model is applied to the 1997 Kagoshima-Ken-Hokuseibu aftershocks. From the RPP sequence in Figure 3b it appears that a subinterval of relative activation is indicated. On the other hand, Figures 4 and 5 indicate relative quiescence. In this particular data set the ETAS fits much better with a large AIC difference, and therefore the relative quiescence is concluded.

6. Data

We mainly use the hypocenter data of the Japan Meteorological Agency (JMA) for the period from 1926 up to the present, occasionally in combination with a sequence of felt/unfelt shocks by certain JMA observatories recorded in the *Kisho-Yoran* (the *Geophysical Review of the JMA*), and the *Zisin-Geppo* (the *Seismological Bulletin of the JMA*). In conjunction with the aftershock data from the JMA hypocenter catalog, undetermined magnitudes of felt/unfelt events are roughly estimated based on the Gutenberg-Richter's relation. Although the detection rate of the earthquakes in and around Japan is heterogeneous not only in the period from 1926 to the present but also in space (particularly between inland and in sea), my preliminary policy is collection of as many aftershock sequences as possible which can be applied by the ETAS model, namely, the data sets consisting of at least 20 to 30 events' occurrence times that are associated with magnitudes. The considered region is throughout Japan and its vicinity except for a few local regions where it is difficult to discriminate aftershocks and swarms by separation into subregions, such as the activity in and around the Izu Peninsula and Izu Islands.

The periods of the study from the main shock occurrence time are set to either of the following three cases: (1) up to the occurrence time of the suspected subsequent large event in the neighborhood (within about 5°). (2) about $10^{0.5M-1}$ days or more for the magnitude M of the main shock [from *Utsu*, 1969], as far as no other conspicuously large event occurred so as not to contaminate the considered aftershock activity, in the case where the background seismicity around source region is active, or (3) the end of the available period in the JMA hypocenter catalog at the date of the analysis (e.g., the end of Febrary 1997 for the 1995 Kobe event) in cases where the background seismicity around the source region is not active. In all cases aftershock events in a sequence appear to be homogeneously detected, that is, the detection rate is independent of lapse time throughout the analyzing time span except for a short span immediately after the main shock. Thus the starting time S in (4) is determined to maintain the homogeneity throughout the period $[S, T]$. The details of considered aftershock sequences such as selected spatial ranges and periods and other parameters are described in Appendix A[1] [*Ogata*, 2000].

Figures 6a and 6b displays epicenters and latitude versus time plots, respectively, of the 76 earthquakes whose aftershocks are studied. Table 1 lists the name, occurrence date, and location of the main shock. For each main shock we prepare occurrence times of aftershocks associated with magnitudes which are not smaller than a suitable threshold magnitude where the sequence in the time span $[S, T]$ for some S is expected to be either complete or homogeneous (i.e., the detection rate is a constant throughout the period of the analysis).

Figures 6a and 6b

Table 1

We will further analyze subsequences of events with larger threshold magnitudes by an increment of $0.2 \sim 0.5$ until the data size becomes too small to be analyzed by the ETAS. From my experience, a longer span of relative quiescence with higher level of threshold magnitude seems to relate to the larger size of the forthcoming suspected event. Therefore the analysis of data with larger magnitude thresholds appears to take on more importance in spite of their smaller data size though the result can be less stable accordingly. As a consequence, for the same main shock, different results can be obtained from aftershock data subsets with different threshold magnitudes. For such a case, the relative quiescence of the aftershock activity is concluded only when plural data sets with different threshold magnitudes have a significant change point which lead

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[1] Supporting Appendix A is available via Web browser or via Anonymous FTP from ftp://kosmos.agu.org, directory "append" (Username="anonymous", Password="guest"); subdirectories in the ftp site are arranged by paper number. Information on searching and submitting electronic supplements is found at http://www.agu.org/pubs/esupp_about.html.

to the relative quiescence in the subsequent time span.

Out of the 76 main shocks, 34 aftershock activities have significant change points, which are followed by relative quiescence. From here on, we call such aftershock activity abnormal in contrast to the normal activity. There are only a few aftershock sequences where the change point was not followed by relative quiescence. This may be owing to the feature of the ETAS which models further clusters (i.e., activation) triggered by large aftershocks. The threshold magnitudes in Table 1 summarize the results. The details on the analysis with corresponding figures for each aftershock sequence are provided in Appendix A [*Ogata*, 2000].

According to the results of the analysis, it is not always clear whether or not the relative quiescence was followed by the occurrence of a large event in the neighborhood, and also there are cases where the normal aftershock activity was followed by a large event in the neighborhood (see Appendix A for details). Here it should be noted that in order to make a definite conclusion regarding the causality between relative quiescence and the occurrence of a subsequent large event, we see no clear-cut thresholds for the timelag and the distance between them. Instead, the conclusion of the causality seems to be conducted only statistically, namely, through the assessment of the probability with regard to the time lag and the distance. This is the reason why we have studied as many aftershock sequences as possible using the ETAS model.

In order to make the probability assessments we collect all large events in and around Japan, even for those that have few recorded aftershocks. Figure 7 shows epicenters and latitude versus time plot of such events as explicitly described below. Here it should be noted that the seismic activity is much higher offshore than on land. Taking this into account, we selected inland events whose size is equal to M_J6.0 or larger and offshore events equal to M_J7.0 or larger. The reason is twofold. First, we consider earthquakes that will cause some destruction in land, and second, aftershocks detected offshore are fewer than those on land of similar size due to low detection capability

Figure 7

owing to the configuration of the seismic network. Indeed, about half of the main shocks of the analyzed aftershock sequences took place on land.

7. Some Statistical Results

For each of the main shocks in Figure 6, we select subsequent earthquakes from the large events in Figure 7 conditional on their sizes being similar to or larger than the main shock. To be precise, the subsequent events are of such magnitude M that $M \geq M_0$–0.2, where M_0 is the magnitude of the main shock. Those subsequent large events relative to each main shock of either normal or abnormal aftershock activity are spatiotemporally superposed, as respectively shown in Figures 8a and 8b, to investigate whether any statistical difference is revealed. Figures 8a and 8b plot the lapse time versus distance of the large subsequent events with about equal or larger size than the main shock (precisely, larger than M_0–0.2), where the origin of the coordinate represents the main shock of the analyzed aftershocks. Figure 8a represents the case where the aftershock sequence has no change point (normal activity), and Figure 8b stands for the case where the aftershock sequence has relative quiescence (abnormal activity). In this manner, the plots of circles are superposed for the 43 main shocks of normal aftershock activity and for the 34 main shocks of abnormal aftershock activity, respectively.

Figures 8a and 8b

Here notice that the abscissa is scaled by square of the distance, being proportional to the area of the disk with the distance for the radius, which was intended to create a display of what should be a uniform distribution in two dimension in the time-distance rectangular region if the subsequent events were independently located with respect to the main shock of the investigated aftershock sequence. However, Figures 8a and 8b display a tendency toward concentration in space because the subsequent events do not appear uniformly distributed but more or less dense toward the left boundary. This is perhaps owing not only to the fact that earthquakes mainly occur in seismic belt along the Japan islands arc but also that the two point correlation function between earthquakes decays inverse power law in distance [e.g., *Kagan and Knopoff*, 1980]. In particular, even taking such trend into account, the concentration for the earlier half period in Figure 8b appears remarkably higher than for the rest of the period and also than for the whole period in Figure 8a. Time series of mean of squares of distances and time series of the number of neighboring pairs (say, within a 3°separation) for each year in the plots of Figure 8b appear to indicate an increase and decrease, respectively, around the first 6 years.

If, for each of the main shocks in Figure 6, all subsequent events of $M_J 6.5$ and larger are instead chosen from the events in Figure 7 to be superposed as shown in Figures 9a and 9b, we see not only the similar weak and strong concentration tendency in the same space-time superposition as stated above but also a diffusing tendency during the first 5 to 6 years of the aftershock activities where relative quiescence is present (Figure 9b). The time series for Figure 9b similar to those for Figure 8b indicate the same change of levels around the first 6 years.

Figures 9a and 9

Now reconsider the subsequent large events which are similar in size to or larger than the concerned main shock. In order to more clearly differentiate the spatial concentrations of the first 6-year and next 14-year time spans, we make histograms of the number of the subsequent events on the annular regions centered at the main shock with the radii split at distances of 1°, 2°, ..., 8° from the epicenter. Then, after taking a ratio of the histogram to the area of each annulus, we divide them by the number of main shocks that have been set to the coordinate origin. Thus we obtain Figures 10a and 10b which show the average number of events per unit area (1° × 1°) for the first 6-year period (Figure 10a) and for the next 14-year period (Figure 10b) from the occurrence time of the main shock.

Figures 10a and

Here the concentration tendency of events for the first 6 years after the relative quiescence is conspicuously higher than the other cases. In contrast, we see similar decreasing histograms with respect to increasing distance not only for the first 6- and second 14-year periods after the normal aftershock activity but also for the second 14 years even after anomalous aftershocks. In particular, the occurrence rate of a large event after anomalous aftershock activity is 0.02 event deg^{-2} yr^{-1} in the region within $\sim$1.0° distance for the first 6 years, which is $\sim$10 times larger than those in the far field. Further, the occurrence rate for the first 6-year period after the abnormal aftershock activity is about several times as large throughout the area of distance up to a few degrees when compared to the other cases in respective period.

This is useful information for the medium-term forecast of a large event. Here we have considered the case of $M \geq M_0 - D$ with $D = 0.2$, but the results do not depend much on the choice of D. For example, the results are very similar in the case of following events whose magnitudes are either equal to or strictly larger than the main shock of the analyzed aftershocks ($D = 0$).

From Table 1 we see that different results for the same main shock can be obtained depending on its aftershock data subsets with different threshold magnitudes. When such inconsistent results are obtained, we first consider that the main shock have anomalous aftershock activity if at least two aftershock data subsets of the same main shock have relative quiescence, as discussed in section 5. Thus the spatial hazard rate in Figures 10a and 10b are estimated by counting the number of subsequent events.

Another way to assess the hazard is through counting the subsequent events relative to each analyzed aftershock sequence data of each threshold magnitude, while allowing the corresponding main shock to repeat. For example, if we have two out of five aftershock data subsets of the same main shock resulting in relative quiescence, then the same subsequent events are counted 2 and 3 times, respectively, in each corresponding distance bin for the estimation of the hazard rate that is conditional on whether or not the data sets have relative quiescence. Thus, altogether, we obtain the histogram by means of the superpositions of the subsequent large events relative to the 100 aftershock data sets of quiescence. Similarly, the other histogram is obtained based on the superposition of the subsequent large events relative to the 159 normal aftershock sequences. Then similarly normalized spatial distributions in Figures 11a and 11b lead to the diagrams similar in shape and sizes to Figures 10a and 10b, respectively.

Figures 11a and

8. Discussions

In practice, we recommend carrying out the analysis of aftershock data subsets of the same main shock with as many threshold magnitudes as possible. Then we estimate the eventual hazard rate by taking the average of the hazard rates in Figures 11a and 11b depending on whether the analyzed aftershock data set of the considered threshold magnitude has relative quiescence or normal activity throughout the whole period, respectively. In any case, it has been demonstrated that relative quiescence can be a helpful factor in discriminating whether or not a large event is more likely to follow in the neighborhood within a 6-year period.

Appendix A [*Ogata*, 2000] provides the estimates of the ETAS coefficients in the corresponding figures, and there are quite a few cases where the p value estimate are smaller than 1. Thus one may suspect that the low p value in the first period inevitably leads the relative quiescence since the continuation of $p < 1$ should generate infinitely many aftershocks. However, it turns out from the analysis by the cross-classified table that the interdependence between the low p value and emergence of the relative quiescence is not so strong. Furthermore, the use of a low initial estimated p value (say, $\hat{p} < 1$ or $\hat{p} < 0.9$) as the discriminative factor instead of the relative quiescence leads to mutually similar estimates of the hazard rate functions unlike the left diagram in Figure 11. That is to say, the low p values cannot be a discriminating factor unlike the relative quiescence, but it is worthwhile to note that the relative quiescence takes place a little over twice as frequently as the normal cases when p is very low (say, $p < 0.9$, though this did not happen often).

It is fair to say that the present analysis is retrospective particularly in the choice of the length of aftershock time span ranging from a few months to a number of years (see section 6). In order to estimate the hazard based on the real-time observation, we need further investigation to make unbiased estimation avoiding potential systematic errors from the present estimate if it exist.

A similar problem arises from the smaller number of the collected aftershock sequences in the earlier period than that of the rest owing to changes in detection rate of earthquakes during the period of study 1925-1999 (see section 6), while the seismicity in and around Japan appears to be more active in the earlier years. Therefore, in order to examine the stability of the features discussed in Figures 8-11 the studied period is divided into the two subperiods at the end of 1960. The concentrating features corresponding to the Figures 8 and 9 remain the same, but the mean rates are different for the periods before and after 1960, as is easily seen from the ratios of number of subsequent earthquakes to that of investigated main shocks in each subperiod. The rates estimated in Figures 10 and 11 appears the average hazard rates of those in the two subperiods. For more accurate estimation of the hazard rates we need to make a similar study using homogeneous data sets which may be possible by considering either rather recent smaller earthquakes or worldwide large and medium size earthquakes.

9. Conclusions

Many aftershock sequences are more complex than the simple inverse power decay represented by the modified Omori formula. The ETAS model, which uses magnitude data in addition to the occurrence times, fits well with various aftershock sequences, including nonvolcanic swarms when the activity pattern is homogeneous throughout the period in and around the source region, namely, when the parameters of the ETAS model are constants (independent of time and location) throughout. Then we are concerned with the seismicity change of aftershock sequences in time which are followed by the relative quiescence, that is, a significant seismicity lowering from that predicted by the ETAS model. The significance of the change is objectively judged by means of the modified AIC for the change point problem.

Using the ETAS model and on the basis of the proposed procedure, 259 aftershock sequences of various threshold magnitudes are investigated for the 76 main shocks of $M6$ class or over that occurred in and around Japan during the last three-quarters century (see Appendix A [*Ogata*, 2000] for details). Relative quiescence is revealed in ~40% of the aftershock sequences, and almost all the others are developed normally; relative activation is rarely found. We have seen that the aftershock activity provides useful information for assessing the probability of a following large event ($M6$ class or over) in the neighborhood. Namely, if the aftershock activity from the first event becomes relatively quiet compared to the expected normal decay, the occurrence rate of a larger event in the neighborhood (within a distance of 3°) is a few times higher during the first decade after the main shock than would be the case for normal aftershock activity.

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Table 1. Studied Aftershocks[a]

Date	Name	M_J	Epicenter	Threshold Magnitudes[b]
	Off the East Coast of Hokkaido (Region A)			
Dec. 04, 1995	Off Iturup Island	7.9	150.1 44.6	(4.0) (4.5) 5.0
Oct. 04, 1994	Hokkaido-Toho-Oki	8.1	147.7 43.4	4.5 5.0 (5.5*A*) 6.0
Aug. 18, 1994	Hokkaido-Toho-Oki	6.4	150.9 45.1	(3.5) (4.0) (4.5)
Jan. 15, 1993	Kushiro-Oki	7.8	144.4 42.9	3.0 3.5 4.0
April 01, 1990	Hokkaido-Toho-Oki	6.0	147.1 42.8	(0.0) (3.6) (3.8) (4.0)
March 21, 1982	Urakawa-Oki	7.1	142.6 42.1	3.3 3.6 4.0 4.2
June 17, 1973	Nemuro-Hanto-Oki	7.4	146.0 43.0	(4.0) (4.5) (4.8) 5.2
March 04, 1952	Tokachi-Oki	8.2	144.1 41.8	0.0 5.0 5.5 6.0
Nov. 26, 1932	Hidaka-Chubu	7.0	142.5 42.4	unfelt (felt) (4.5)
	Off the East Coast and Inland of Tohoku District (Region B)			
Aug. 11, 1996	Onikobe	5.9	140.6 38.9	2.5 3.1 3.5 (3.8) (4.0)
Jan. 07, 1995	Sanriku-Haruka-Oki (secondary)	7.2	142.3 40.2	3.0 3.5 4.0 4.5
Dec. 28, 1994	Sanriku-Haruka-Oki (long)	7.5	143.7 40.4	4.0 4.5 5.0 5.4
Dec. 28, 1994	Sanriku-Haruka-Oki (short)	7.5	143.7 40.4	4.0 (4.5) (4.9)
April 08, 1994	Sanriku-Oki	6.6	144.0 40.6	3.5 4.0
Dec 28, 1992	Sanriku-Oki	5.9	142.6 38.9	(3.0) (3.5) (3.9) (4.4)
July 18, 1992	Sanriku-Haruka-Oki	6.9	143.7 39.4	(3.5) (3.7) 3.8 4.0 (4.5) 5.0
Nov. 02, 1989	Iwate-ken-Oki	7.1	143.1 35.8	4.0 4.5 5.0

Table 1. (continued)

Date	Name	M_J	Epicenter	Threshold Magnitudes[b]
Jan. 09, 1987	Iwate-Ken-Hokubu	6.6	141.8 39.8	0.0 3.0
Jan. 19, 1981	Miyagi-Ken-Oki	7.0	143.0 38.6	0.0 3.6 4.1 4.6
June 12, 1978	Miyagi-Ken-Oki	7.4	142.2 38.2	3.4 4.0 4.2 (4.5) (4.9)
Feb. 20, 1978	Near Ojika-Peninsula	6.7	142.2 38.8	3.0 3.3 (3.5)
June 12, 1968	Tokachi-Oki (Southern)	7.2	143.1 39.4	4.5 5.0 5.5
May. 16, 1968	Tokachi-Oki (Northern)	7.9	143.6 40.7	4.5 5.0 5.5 5.9
April 30, 1962	Miyagi-Ken-Hokubu	6.5	141.1 38.7	(0.0) 4.0
March 21, 1960	Iwate-Ken-Oki	7.2	143.4 39.8	0.0 4.4 4.9 5.4
Nov. 05, 1938	Shioya-Oki-Swarm	7.5	142.2 37.3	4.5 4.7 (5.0) 5.5
March 03, 1933	Sanriku-Oki	8.1	144.5 39.2	(0.0A)(6.0N)5.5(5.8A)(6.0)(6.2)
Nov. 04, 1931	Iwate-Ken-Tobu	6.5	141.7 39.5	(unfelt) (felt) (felt$A$) 4.0
May 27, 1928	Iwate-Ken-Oki	7.0	143.3 40.0	0.0 5.1 (5.3) (5.5)
	Eastern Limb in Sea of Japan (Region C)			
Apr. 01, 1995	Niigata-Ken-Chubu	5.5	139.3 37.9	(2.8A) 3.0 3.2 (3.5)
July 12, 1993	Hokkaido-Nansei-Oki	7.8	139.2 42.8	(4.0A) 4.5 5.0
Feb. 07, 1993	Noto-Hanto-Oki	6.6	137.3 37.7	(3.0) 3.5 (4.0)
May 26, 1983	Nihonkai-Chubu	7.7	139.1 40.4	4.0 4.5 (5.0) (5.2) (5.3)
June 16, 1964	Niigata earthquake	7.5	139.2 38.4	felt 4.0 4.5 5.0
May 07, 1964	Oga-Hanto-Oki	6.9	139.0 40.3	unfelt felt 0.0

Table 1. (continued)

Date	Name	M_J	Epicenter	Threshold Magnitudes[b]
May 01, 1939	Oga-Hanto-Oki	6.8	139.5 40.1	0.0 4.1
Kanto and Tokai District and Their Offshore Regions (Region D)				
June 01, 1990	Chiba-Ken-Hokubu	6.0	140.7 35.7	2.0 2.5 3.0
March 06, 1989	Chiba-Ken-Hokubu	6.0	140.7 35.6	(2.0) (2.5) 3.0 (3.5)
Dec. 17, 1987	Chiba-Ken-Toho-Oki	6.7	140.5 35.4	(2.5) (3.0) (3.5) (4.0)
Aug 08, 1983	Yamanashi-Ken-Tobu	6.0	139.0 35.5	2.5 (2.7) (2.9) (3.0)
July 23, 1982	Ibaragi-Ken-Oki	7.0	142.0 36.2	3.2 (3.7) 4.2
Dec. 04, 1972	Hachijo-Jima-Oki	7.2	141.1 33.2	3.6 4.0 4.5
Feb. 29, 1972	Hachijo-Jima-Oki	7.1	141.3 33.2	(3.6) (4.0) (4.6)
Nov. 26, 1953	Boso-Oki	7.4	141.7 34.0	0.0 5.0 5.5
Dec. 26, 1949	Imaichi	6.4	139.8 36.6	felt 4.2
May 23, 1938	Ibaragi-Ken-Oki	7.3	141.6 36.7	0.0 4.1
Sept. 21, 1931	Saitama-Ken-Seibu	6.9	139.2 36.2	0.0 3.0 3.5 (3.8) (4.0)
Hokuriku and Chubu District (Region E)				
Sept. 14, 1984	Nagano-Ken-Seibu	6.8	137.6 35.8	3.5 4.0 4.5
Oct. 07, 1978	Nagano-Ken-Swarm	5.3	137.5 35.8	(2.5) (3.0) 3.5
Sept. 09, 1969	Gifu-Ken-Chubu	6.6	137.1 35.8	0.0 3.9
March 27, 1963	Echizen-Misaki-Oki	6.9	135.8 35.8	0.0
Aug. 19, 1961	Kita-Mino	7.0	136.8 36.0	0.0

Table 1. (continued)

Date	Name	M_J	Epicenter	Threshold Magnitudes[b]
March 07, 1952	Daishoji-Oki	6.5	136.2 36.5	(felt) (0.0) (4.2) (4.5)
June 28, 1948	Fukui	7.1	136.2 36.2	felt 0.0 3.5 4.0 (4.5) 4.7
July 15, 1941	Nagano	6.1	138.2 36.7	(felt) (0.0)
	Kinki District and Offshore Regions (Region F)			
Jan. 17, 1995	Hyogo-Ken-Nanbu	7.2	135.0 34.6	3.0 3.5 4.0 4.2
Nov. 09, 1994	Inagawa Swarm	4.0	135.4 34.9	(2.0) (2.3) (2.5) (2.6)
May 30, 1984	Yamasaki Fault	5.6	134.6 35.0	(2.5) 2.6 3.0
Dec. 21, 1946	Nankaido	8.0	135.6 33.0	(4.0) (4.5) (4.9) 5.0 5.5
Jan. 13, 1945	Mikawa	6.8	137.1 34.7	(felt) (0.0) (4.4) 4.8
Dec. 07, 1944	Tonankai	7.9	136.6 33.8	4.0 (4.5) (4.8) 5.0
March 07, 1927	Kita-Tango	7.3	135.2 35.5	0.0 4.5
May 23, 1925	Tajima	6.8	134.8 35.6	(felt) (5.0)
	Southwestern Japan (Region G)			
June 25, 1997	Yamaguchi/Shimane-Ken Border	6.1	131.7 34.5	(2.6) (3.0) 3.4
May 13, 1997	Northern Satsuma	6.2	130.3 31.9	(2.5) 2.8 3.0 3.3
March 26, 1997	Northern Satsuma	6.5	130.4 32.0	(2.7) (3.0) (3.5)
Oct. 18, 1995	Amami-Oshima-Oki	6.6	130.4 28.0	(3.5) 3.8 4.0 4.5
March 18, 1987	Miyazaki-Ken-Oki	6.6	132.1 32.0	2.5 2.9 3.4
Aug. 07, 1984	Miyazaki-Ken-Oki	7.1	132.2 32.4	2.8 3.3 3.8

Table 1. (continued)

Date	Name	M_J	Epicenter	Threshold Magnitudes[b]
Oct 31, 1983	Tottori-Ken	6.2	133.9 35.4	(2.3) (2.5) (2.7) (2.8) 3.0
Mar 03, 1980	Okinawa-Hokusei-Oki	6.7	126.6 27.0	(0.0) (4.2) (4.5)
June 04, 1978	Shimane-Ken-Chubu	6.1	132.7 35.1	0.0 3.3 3.7
Aug. 06, 1968	Ehime-Ken-Seigan	6.6	132.4 33.3	3.5 4.0
July 27, 1955	Tokushima-Ken-Nanbu	6.4	134.3 33.8	0.0 3.0
Sept. 10, 1943	Tottori	7.4	134.1 35.5	(4.0) (4.4) (4.7) 5.0
March 04, 1943	Eastern Tottori	6.2	134.2 35.4	(felt) (3.6)

[a] Regions A-G into which Japan and its vicinity are expediently divided for the present analysis are also shown in Figure 6.

[b] The numbers in parentheses, or followed by *A* or *N* indicate that a sequence of aftershocks of that magnitude or larger has a significant change point followed by the relative quiescence, relative activation, and neither of them, respectively. The remaining values indicate that the activity was normal for the whole investigated period, namely, no significant change point is found. The threshold magnitude indicated by (0.0) or 0.0 means inclusion of all events whose magnitudes are not determined but locations are identified in the JMA hypocenter catalog. The threshold magnitude indicated by (felt) or felt and (unfelt) or unfelt mean the data set which include all felt shocks and unfelt events in addition to felt shocks, respectively, listed in the *Kisho-Yoran* or *Zisin-Geppo* together with all available events from the JMA catalog: see Appendix A [*Ogata*, 2000] for the details of the aftershock data selection and the results with corresponding figures attached for each data set.

Figure Captions

Figure 1. A schematic graph of a complex aftershock sequence. The dashed line represents the curve for the modified Omori formula fitting the whole sequence. The hatched area indicates the secondary aftershocks triggered by shock 3 (from *Utsu* [1970]).

Figure 2. Cumulative curves and magnitude versus time (M-T) plot of the aftershocks ($M \geq 3.0$) of the 1995 Hyogo-Ken-Nanbu (Kobe) earthquake of $M_J 7.2$ during the period of 773 days following the main event: (a) ordinary time and (b) transformed time (see text) with the indications of estimated ETAS coefficients (MLE) and the AIC value in the fitted interval. Marks on both the linear and transformed time axes indicate a month interval. Vertical dotted lines stand for the starting time $S = 0.02$ days of the fitted interval, though it is barely seen in Figure 2a, to avoid the affection of the missing aftershocks immediately after the main shock (see section 3). The dashed lines below the horizontal dotted lines, which are explained in the Figure 5 caption, show no significant change point.

Figure 3. Cumulative curves and M-T plot of aftershocks ($M \geq 2.7$) of the 1997 Kagoshima-Ken-Hokuseibu (Satsuma) earthquake of $M_J 6.5$ up until the occurrence of the second Satsuma earthquake of $M_J 6.2$: (a) ordinary time on a linear scale in days, and (b) transformed time based on the integration of the modified Omori function. Conspicuous clusters are indicated by the arrows corresponding to large aftershocks.

Figure 4. Fitting of (a and b) the single ETAS model and (c and d) the two-stage ETAS models to the same aftershock data as that in Figure 3. The smoother thin curve in Figure 4a and the straight line in Figure 4b represent the same predicted cumulative function of the ordinary linear and transformed times, respectively. The smoother thin curve in Figure 4c and straight line in Figure 4d show the same predicted cumulative curve estimated from the data in the first period up until a suspected change point (vertical dotted line). The extrapolation shows that the events in the second period are substantially fewer than expected.

Figure 5. Change point analysis of the same aftershock as in Figures 3 and 4. Figures 5a and 5b are the same as those of Figures 2a and 2b except for the following: The dashed lines in Figure 5a stand for the time series $\xi(t)$ defined in (7) for time t during the whole period $[S, T] = [0.03, 47.88]$ days. The maximum of $\xi(t)$ at $t = T_c$=5.39 days exceeds the level of the horizontal dotted line $k(N) = 3.15$ for N=521, showing the significant change point. Here the horizontal solid line displays a reference level corresponding to $\xi(t) = 0$ and the numbers in the right sides of the ordinates indicate the values of the time series $\xi(t)$. The dashed lines in Figure 5b show the calculated $\xi(t)$ for time t during the period $[S, T_c]$, which are below the level of dotted line $k(N) = 3.07$ for the number of events N=309 in the same period, in which no further significant change points are shown.

Figure 6. Map of main shocks whose aftershock sequences are analyzed. (a) Locations of the epicenters with indication of the regions corresponding to those in Table 1 and (b) latitude versus time plot.

Figure 7. Large earthquakes (land, $M_J \geq$6.0; sea, $M_J \geq$7.0) used in the investigation of space-time distances relative to the main shocks of the analyzed aftershock sequences: (a) epicenters and (b) latitude versus time plot.

Figure 8. Superposed plots of the time difference versus distance of subsequent large events from the main shock of the investigated aftershocks: (a) superposition for the 43 main shocks whose aftershock sequences have no change point, and (b) superposition for the 34 main shocks whose aftershock sequences show relative quiescence. Only events with sizes similar to or larger than the main shock (specifically, $M \geq M_0$–0.2) were selected from the events in Figure 7. The abscissa is scaled by the square of the distance so as to be proportional to the area of the disk with the given distance as radius. A notably strong concentration in distance occurs during about the first 6 years in Figure 8b compared to the rest 14 years and also to all 20 years in Figure 8a.

Figure 9. Diagrams obtained by the same procedure as those in Figure 8 except that the subsequent events of $M \geq$6.5 are selected from the events in Figure 7 instead of the events of magnitude M_0–0.2 or larger. The diffusing feature and higher concentration in distance during about the first 6 years in Figure 9b appear clear.

Figure 10. Average numbers of the subsequent large earthquakes per unit area ($1° \times 1°$) against distance from the main shock of the investigated aftershock sequence. Earthquakes occurring within the (a) first and (b) second 10-year periods after the main event. The dashed lines connecting the symbols "R" and "o" stand for the cases of anomalous (with relative quiescence) and normal aftershock activity, respectively. See text for the estimation procedure.

Figure 11. Alternative estimate of the occurrence rate of a subsequently large event per the unit area against distance from the main shock. See text for the estimation procedure. Caption is the same as for Figure 10.