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Seismicity Pattern Changes Prior to Large Earthquakes -An Approach of the RTL Algorithm

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ABSTRACT

A statistical method, which is called the Region-Time-Length (RTL) algorithm and takes into account information such as magnitude, occurrence time and place of earthquakes, was applied to earthquake data to investigate seismicity pattern changes prior to large earthquakes. Based on the RTL algorithm and some newly developed parameters such as the *Q*-parameter (average of the RTL values over some time window) and *S*-parameter (an index of seismic activation), I quantified both the temporal and spatial characteristics of seismicity pattern changes in various tectonic regions. The results indicated that seismic quiescence anomalies generally started a few years before the occurrence of the earthquakes and lasted from 1 to 2.5 years. The duration of the subsequent stage of seismic activation generally lasted several months. The linear dimension of the quiescence zone reached a few hundred kilometers (several times the rupture dimension of the mainshock), while the activation zone was generally in order of several tens of kilometers (comparable to the rupture dimension). An earthquake is most likely to occur once the relevant source region has passed through the quiescence and activation stages. Close investigation of possible artifacts due to the selection of model parameters and the changes of seismological networks are important in identifying real seismicity changes from man-made ones. Further stochastic testing using random earthquake catalogs was also done and it supports that the anomalies revealed in my works are significant. Besides studying on seismicity changes before large earthquakes, I also performed the first test of the above statistical method for investigating seismicity changes of earthquake swarms. It indicated that an increased RTL parameter would be a new potentially useful index for the risk alarm of earthquake swarms.

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(Key words: Seismicity, Seismic quiescence, Seismic activation, Earthquake swarm, RTL algorithm.)

1. INTRODUCTION

Although whether or not an earthquake can be predicted is highly controversial (Geller et al. 1997; Wyss 1997), some scientists are continuing to find valuable earthquake precursors. Because seismicity precursors have been tested over many years and some positive examples have been obtained (Kossobokov and Keilis - Borok 1990; Sobolev and Tyupkin 1997 1999; Wyss and Martirosyan 1998; Wyss and Matsumura 2002; Öncel and Wyss 2000; Öncel and Wilson 2002; Öncel et al. 1996; Sobolev et al. 2002; Huang and Nagao 2002; Huang et al. 2001, 2002), seismicity analysis plays an important role in earthquake prediction in the intermediate-term.

Laboratory rock experiments indicate the acoustic emissions may accelerate as loading increases. However, the number of relatively weak signals tends to decrease after loading reaches a maximum, because small cracks are no longer generated due to partial reduction in stress. During the final stage before the main rupture, acoustic activity increases again. In other words, acoustic emission passes through stages of quiescence and activation prior to the main rupture (Sobolev 1995).

Field seismological observations also indicate the existence of quiescence and activation stages of seismicity in the rupture region of strong earthquakes. Among all seismicity changes, seismic quiescence, which is defined as a decrease of mean seismicity compared to the preceding background rate in and around focal areas, may be one of the most promising intermediate-term precursors and has received much attention (e.g., Mogi 1979; Wyss and Habermann 1988; Wyss and Martirosyan 1998; Wiemer and Wyss 1994; Katsumata and Kasahara 1999).

A statistic method was developed recently to investigate the characteristics of seismicity changes, including both quiescence and activation patterns (e.g., Sobolev and Tyupkin 1997; 1999; Huang et al. 2001). This method is called an RTL algorithm, where the name RTL comes from R: Region (epicentral distance), T: Time interval, and L: Length (rupture size). The RTL algorithm is based on physical modeling regularities, and the RTL is a parameter reflecting the combination of three functions: distance, time and rupture length, respectively. All three parameters (time, place and magnitude) of earthquakes are taken into account with a weighted coefficient in this algorithm (see Section 2.1).

Some recent studies in Russia, Italy, Japan and Turkey indicate that the RTL algorithm is a useful tool to reveal seismicity precursor for strong earthquakes (Di Giovambattista and Tyupkin 1999, 2001; Huang and Sobolev 2001, 2002; Huang et al. 2001, 2002).

In this paper, I will first introduce the basic idea of the RTL algorithm, some related new parameters that can quantify the spatial characteristics of quiescence and activation anomalies of seismicity, and the pre-process (aftershock elimination and completeness analysis) of the earthquake data; then, I will summarize the main results obtained in various tectonic regions; and finally, I will discuss possible artificial effects (e.g., changes of seismological network or selections of model parameters), the significance of anomalies of seismicity changes, and the potential application of the algorithm.

2. METHODS AND DATA ANALYSIS

2.1 RTL Algorithm

The RTL algorithm (Sobolev and Tyupkin 1997; Huang et al. 2001) takes into account weighted quantities associated with all three parameters (time, place and magnitude) of earthquakes. The basic assumption of the RTL algorithm is that the influence weight of each prior event on the main event under investigation may be quantified in the form of a weight. Weighting becomes larger when an earthquake is larger in magnitude or is closer to the investigated place or time. Figure 1 gives the principle of the RTL algorithm. A RTL parameter is defined as the product of the following three functions: epicentral distance, *R(x, y, z, t)*; time, *T(x, y, z, t)*; and rupture length, *L(x, y, z, t)*, where *t* is time,

$$
\begin{aligned}
R(x,y,z,t) &= \left[\sum_{i=1}^{n} \exp\left(-\frac{r_i}{r_0}\right)\right] - R_{bk}(x,y,z,t)\,, \\
T(x,y,z,t) &= \left[\sum_{i=1}^{n} \exp\left(-\frac{t-t_i}{t_0}\right)\right] - T_{bk}(x,y,z,t)\,, \\
L(x,y,z,t) &= \left[\sum_{i=1}^{n} \left(\frac{l_i}{r_i}\right)\right] - L_{bk}(x,y,z,t)\,,
\end{aligned}
\tag{1}
$$

where l_i is the rupture dimension (a function of magnitude M_i), t_i the occurrence time of the *i*th earthquake, r_i the distance from the position *(x, y, z)* to the epicenter of the ith event; r_0 and t_0 are a characteristic distance and time-span, respectively; *n* is the number of events satisfying some criteria, e.g., $M_i \ge M_{\min}$ (M_i is the magnitude of the *i*th earthquake and $M_{\min}$ is the cut-off magnitude ensuring the completeness of the earthquake catalog), $r_i \le R_{\max} = 2r_0$ and $(t - t_i) \le T_{\max} = 2t_0$; $R_{bk}(x,y,z,t)$, $T_{bk}(x,y,z,t)$ and $L_{bk}(x,y,z,t)$ are the trends (background values) of *R(x, y, z, t)*, *T(x, y, z, t)* and *L(x, y, z, t)*, respectively. The *R(x, y, z, t)*, *T(x, y, z, t)* and *L(x, y, z, t)* are three dimensionless functions and are further normalized by their standard deviations, σ_{R}, σ_{T} and σ_{L}, respectively. The product of the above three functions is calculated as the RTL parameter, which describes the deviation from the background level of seismicity and is in units of the standard deviation, $\sigma = \sigma_{\mathrm{R}}\sigma_{\mathrm{T}}\sigma_{\mathrm{L}}$. A negative RTL means a lower seismicity compared to the background rate around the investigated place, and a positive RTL represents a higher seismicity compared to the background. In this study, the temporal variation of the RTL curve is obtained by changing the calculated time, *t* in Eq. (1) at a step of 10 days.

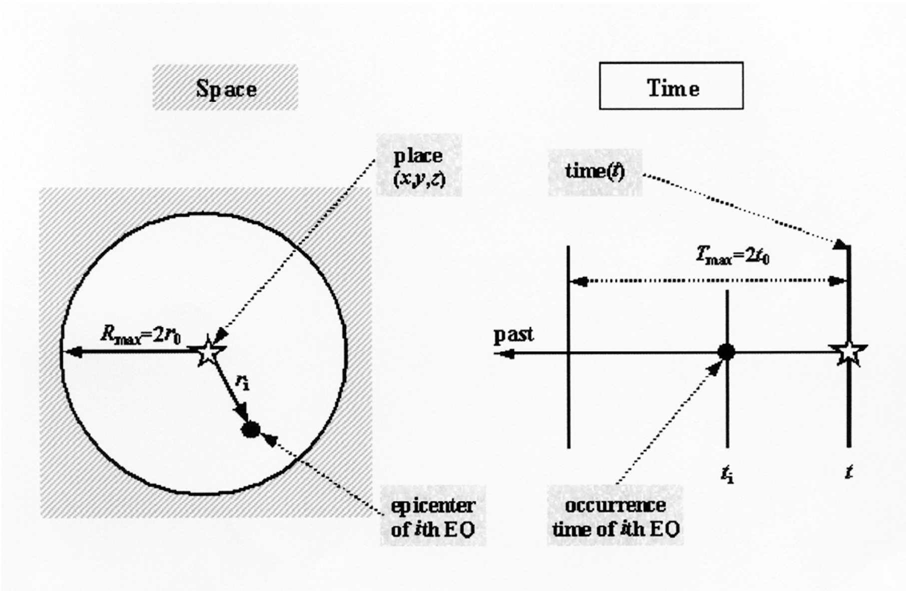

Fig. 1. A sketch of the RTL algorithm. The influence weight of the ith prior event on the main event under investigation becomes larger when the earthquake is larger in magnitude (M_i) or is closer to the investigated place *(x, y, z)* or time *(t)*.

2.2 *Q* - Parameter

A newly developed parameter $Q(x,y,z,t_1,t_2)$ (Huang et al. 2002), an average of the RTL values over some time window $[t_1, t_2]$, was adopted to quantify the seismic quiescence at position *(x, y, z)* during $[t_1, t_2]$. The parameter $Q(x,y,z,t_1,t_2)$ is defined as:

$$Q(x,y,z,t_1,t_2) = \frac{1}{m}\sum_{i=1}^{m} RTL(x,y,z,t_i), \qquad (2)$$

where t_i is the time in the window $[t_1, t_2]$, $RTL(x,y,z,t_i)$ is the RTL parameter calculated as the product of the three functions in Eq. (1) using the earthquakes in a cylindrical volume, and *m* is the number of data points of RTL (RTL parameter is calculated at a step of 10 days in this study) available in $[t_1, t_2]$. In this way, one can obtain the spatial distribution of seismic quiescence as a function of position. A sketch of the above approach is given in Fig. 2.

2.3 *S* - Parameter

Another parameter was developed to reveal the spatial distribution of anomaly of seismic activation (increase of seismicity). A simple assumption was made that the rupture area, S_i of the ith event with magnitude M_i is proportional to $E_i^{2/3}$, where E_i is the seismic energy estimated by the following empirical relation (Kasahara 1981),

$$\log E_i(\mathrm{J}) = 1.5M_i + 4.8 . \quad (3)$$

For convenience, the effective rupture area, S_{eff} was defined as

$$S_{eff} = \frac{1}{\Delta T}\sum_i \frac{S_i}{S_{ref}} = \frac{1}{\Delta T}\sum_i 10^{(M_i - M_{ref})} , \quad (4)$$

where ΔT is the time interval of interest and S_{ref} is the rupture area corresponding to a reference magnitude, M_{ref} . A tentative reference magnitude of $M_{ref} = 5$ was used in this study, for the simplicity of calculation. Note that M_{ref} is introduced to normalize the calculation only and has no influence on the result. The increase of the effective rupture area during a certain time interval, ΔT compared to the averaged background during the background period, T_{bk} (see Fig. 2) would be an index describing the activation level of seismicity. In this study, $\Delta S_{eff} = S_{eff} - S_{bk}$ was chosen as a parameter of the seismic activation, where S_{eff} is the effective rupture area in an investigated activation period, ΔT and S_{bk} is the averaged background one, which can be calculated by Eq. (4) after replacing ΔT by the period of background, T_{bk}.

2.4 Data Analysis

In the first step, I eliminated aftershocks from the seismological catalogs using the program written by V.B. Smirnov on the basis of the algorithm of Molchan and Dmitrieva (1992).

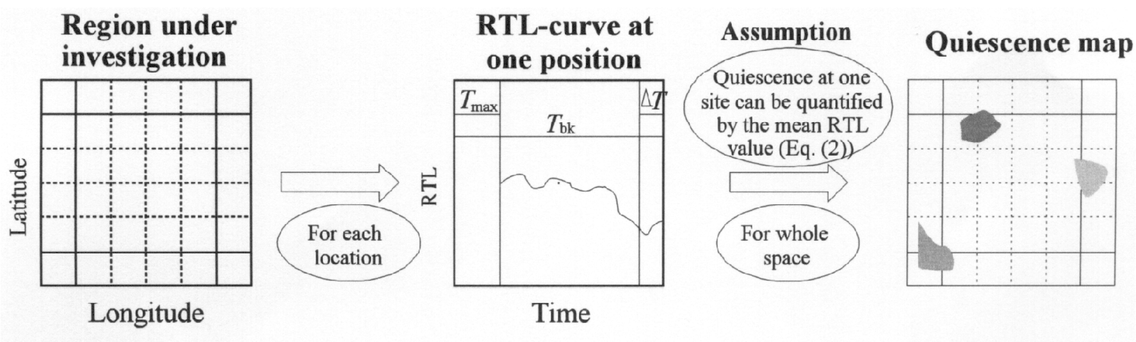

Fig. 2. A sketch map quantifying the spatial distribution of seismic quiescence. The middle-panel shows the RTL-curve at one site investigated, where T_{bk} is the total background time for the RTL calculation, $T_{\max}$ is the threshold time window, and ΔT is the time window investigated for seismic quiescence.

The principle of separating aftershocks from the rest of events, which are called background, is based on the comparison of their functions and their distribution in time and space. Background events are assumed to be distributed evenly. Aftershocks are assumed to have a bell - shaped (Gaussian) distribution on the plane (only earthquakes epicenters are taken into account) and are distributed in time according to the Omori law (Omori 1900). The parameters of those distributions are estimated iteratively as aftershocks are separated. As a criterion on the basis of which an event is referred to a background events group or to aftershocks the requirement of equal probabilities of classification errors is applied, i.e., classifying a true aftershock with background events and including a true background event into the aftershock group. Thus the total number of classification errors is minimized and mathematical expectation is achieved of the equality of the number of aftershocks and their actual value. The algorithm efficiency was tested by Smirnov (1998), who compared aftershock sequences obtained from regional catalogs with the use of this algorithm, and aftershocks catalogs compiled independently by other authors. The discrepancy of the number of aftershocks obtained is approximately 5%.

After eliminating aftershocks from the earthquake catalog, I evaluated the completeness of this catalog using the algorithm developed by Smirnov (1998). The principle of this algorithm is as follows.

The evaluation of the completeness of the earthquake catalog is based on the histograms of earthquake distribution by magnitude. The problem is to find the minimal value $M_{\min}$ with which the recurrence plot is linear in the range of $M \geq M_{\min}$. To solve this problem, all increasing values of $M_{\min}$ are sorted out. The step of sorting out of $\delta M_{\min}$ should be commensurable with the magnitude assessment error in the catalog. A constant step $\delta M_{\min} = 0.1$ was assumed in the program. The initial value $M_{\min} = M_{\min 0}$ may be reasonably arbitrary but it should not exceed the magnitude which is associated with the distribution histogram maximum.

First, the hypothesis of the rectilinear character of the empirical recurrence plot was tested. This test was based on verification of the hypothesis of the agreement of the empirical distribution of earthquakes by magnitudes presented by histogram with the theoretical distribution based on the Gutenberg - Richter relation. If the hypothesis of agreement is accepted on the selected level of significance, $M_{\min}$ is the required assessment of the representative magnitude (i.e., the cut - off magnitude for a complete catalog). In this case, the procedure is over.

The deviation of the recurrence plot from a straight line can be determined both by a "bend" on the earlier magnitudes (non - representative character of data) and a full-scale character (the real curvature of the graph due to natural properties of seismological process in the Earth). The nature of the curvature of the plot is defined with the next step of the procedure. First, the parameters of recurrence law in the range of $M \geq M_{\min} + \Delta M$ (ΔM is a step being chosen to obtain output result. $\Delta M = 0.1$ was chosen in this study) are estimated using the maximum likelihood method. From those parameters, the number of events N_T is calculated in the range of $[M_{\min}, M_{\min} + \Delta M]$, i.e., the recurrence plot is extrapolated to $M_{\min}$ and this "theoretical" number of events is compared to the observed number of earthquakes $N_N(M_{\min})$. The condition $N_N(M_{\min}) < N_T$ is tested on the basis of statistics on the selected level of significance. If $N_N(M_{\min}) < N_T$, then the non - representative character of events of magnitude Mmin is assumed to have caused the deviation of the plot. In this case, the value of $M_{\min}$

is increased by $\delta M_{\min}$ and the whole procedure is repeated. If the condition $N_N(M_{\min}) < N_T$ is not fulfilled statistically, then the hypothesis is assumed of the full-scale character of the curvature of the recurrence plot. In this case, the procedure is stopped and a corresponding mark is entered into the file.

The above - considered algorithm was realized by V.B. Smirnov as a set of programs, which allow making assessments of the representative character of earthquake catalogs in varying time intervals and in desired spatial cells. The application of the algorithm of the completeness assessment to a number of regional catalogs testified its efficiency (Smirnov 1998).

3. SEISMICITY PATTERN CHANGES

The RTL algorithm has been applied to seismological catalogs to investigate the seismicity pattern changes of some strong earthquakes in Russia, Italy, Japan and Turkey (Sobolev and Tyupkin 1997, 1999; Di Giovambattista and Tyupkin 1999, 2001; Huang and Nagao 2002; Huang and Sobolev 2002; Huang et al. 2001, 2002). The brief results of these previous works are summarized in this section. Table 1 gives a summary of the main results of the investigated earthquakes in Russia, Japan and Turkey.

3.1 Earthquakes in Russia

As introduced in the previous section, the rupture length *li*, which is used in calculating RTL parameter [see Eq. (1)], is estimated by empirical relation in the study region. The rupture length in Kamchatka can be estimated by following empirical relation (Riznichenko 1976),

$$\log l_i(km) = 0.244 K_i - 2.266, \tag{5}$$

where K_i is the energy class.

For calculation of the trend of the R_{bk}, T_{bk}, and L_{bk} functions in Eq. (1), the period of the catalog should be long enough compared with the duration of the expected anomalies of quiescence and foreshock activation. In the course of the analysis of Kamchatka earthquakes between 1992 and 1997, for example, the regional catalog was used, which provided all earthquakes with $M \geq 3$ since 1962. The aftershocks were eliminated from this catalog using the program written by V.B. Smirnov on the basis of the algorithm developed by Molchan and Dmitrieva (1992) (also see Section 2.4).

Kamchatka is among the most hazardous areas of Russia. The Pacific Benioff zone accumulated enough elastic energy to produce an earthquake with $M > 8$ (Fedotov et al. 1993). The Gulf of Avache is a very likely location for the above event. Three earthquakes occurred in the gulf in 1992 and 1993: on March 2, 1992 (52.92°N, 159.89°E, M = 7.1), June 8, 1993 (51.25°N, 157.77°E, M = 7.4), and November 13, 1993 (51.79°N, 158.83°E, M = 7.1). The focal mechanisms showed that all the three events are reverse faults with the nodal planes oriented along the Benioff zone. Figure 3 gives the temporal variations of the RTL parameters (in units of the standard deviation, σ) at the epicenters of the above three large earthquakes on March 2, 1992 (Fig. 3a), November 13, 1993 (Fig. 3b) and June 8, 1993 (Fig. 3c), respectively (Sobolev and Tyupkin 1997). The RTL parameters indicated that all three earthquakes were preceded by significant quiescences. Besides the above three earthquakes, I also marked in Fig. 3 by thinner arrows the occurrence time of the other large earthquakes with $M \geq 5.9$ at distances comparable with the source dimensions of earthquakes under study. Figure 3 shows that these earthquakes were generally preceded by lower anomalies of quiescence, although some events were not preceded by any anomalies.

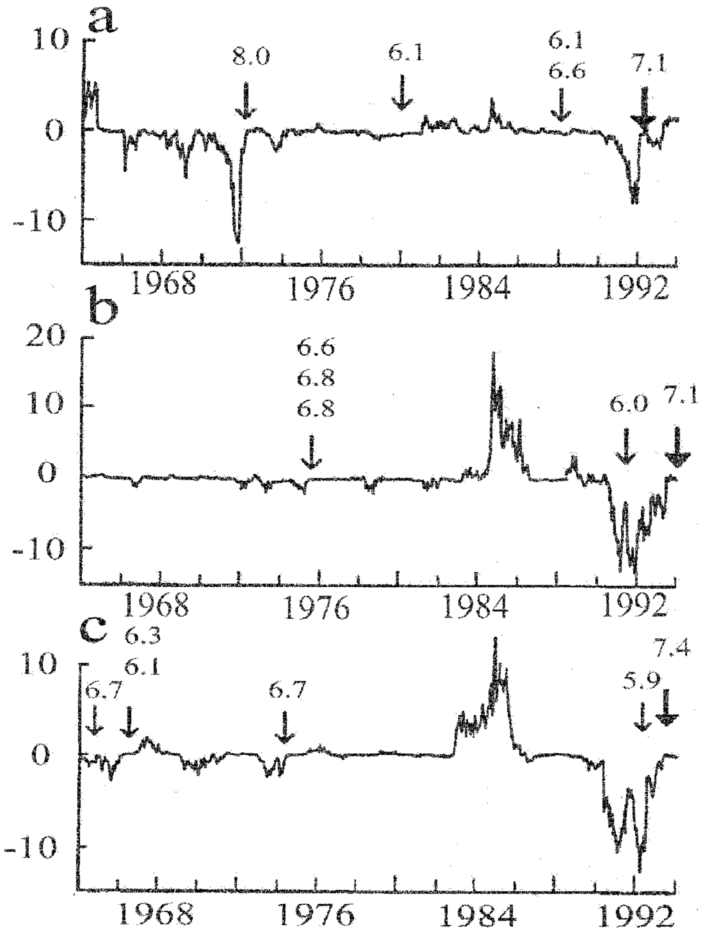

Fig. 3. Variations of the RTL parameters (in unit of the standard deviation, σ) at the epicenters of three large earthquakes in Kamchatka on (a) March 2, 1992, (b) November 13, 1993, and (c) June 8, 1993 (modified after Sobolev and Tyupkin 1997).

The initial test of RTL algorithm indicated that strong earthquakes with $M > 7$ in Kamchatka had been preceded by seismic quiescence followed by foreshock activation (Sobolev and Tyupkin 1997, 1999; also see Table 1). The significant quiescence stages started a few years before the events and lasted from 1 to 2.5 years. The values of deviation from the background exceeded several times the standard deviation.

Table 1. A summary of the main results of the investigated earthquakes in Russia, Japan and Turkey (Sobolev and Tyupkin, 1997; 1999; Huang and Nagao, 2002; Huang et al. 2001; 2002). In the early studies, the minimum of RTL values (RTL_{mi}) in the investigated quiescence period was used to quantify spatial anomaly of seismic quiescence. Recent study (Huang et al. 2002) indicated that the Q - parameter (an average of RTL values in the investigated quiescence period) is a better parameter than the RTL_{mi} - parameter. It should be mentioned that the Q - parameter has quite similar pattern to the RTL_{mi} - parameter. So the RTL_{mi} - parameter is replaced by the Q - parameter in our recent study on seismic quiescence. Different from the RTL_{mi} and the Q - parameter, the S - parameter was used to quantify the spatial anomaly of seismic activation.

Investigated earthquake	**Investigated parameters**	**Seismic quiescence**		**Dimension of anomaly of seismic activation (S-map)**
		Duration	**Dimension of anomaly**	
Kamchatka: March 2, 1992, $M = 7.1$; November 13, 1993, $M = 7.1$; June 8, 1993, $M = 7.4$; December 5, 1997, $M = 7.7$	RTL, RTL_{min}, S	1-2.5 years	100-200 km	Several tens of kilometers
Kobe: January 17, 1995, $M = 7.2$	RTL, RTL_{min}, S	~1 year	~300 km	Several tens of kilometers
Tottori: October 6, 2000, $M = 7.3$	RTL, Q	~1 year	~200 km	
Izu: swarm in 2000	RTL, Q	~1.4 years	~100 km	
Izumit: August 17, 1999, $M = 7.4$	RTL, Q	~1 year	~150 km	

3.2 Earthquakes in Japan

Rupture length in Japan can be estimated by the following empirical relation (Kasahara 1981),

$$\log l_i(km) = 0.5M_i - 1.8. \quad (6)$$

3.2.1 Tottori Earthquake (*M* = 7.3, October 6, 2000)

After eliminating aftershocks and analyzing the completeness of JMA earthquake data in time and space domain based on the approach in Section 2.4, I chose all events with a magnitude larger than 2.5 in the JMA catalog during the period of January 1975 to December, 2000 in the calculation of the RTL parameter at the epicenter (see details in Huang and Nagao 2002). In order to investigate the spatial characteristics of seismicity patterns, I discussed the seismicity changes based on the RTL parameters in the region with longitude between 131.00°E and 135.50°E and latitude between 34.75°N and 37.00°N for the following reasons: (1) the completeness of the JMA earthquake catalog can be ensured for a threshold magnitude of 2.5, which is used in this study, and (2) the 2000 Tottori earthquake is the only event with $M \geq 6.5$ in this region between January, 1975 and December, 2000.

Figure 4 gives the temporal variation of the RTL parameter at the epicenter (133.35°E, 35.27°N) of the $M = 7.3$ Tottori earthquake. It shows that a seismic quiescence started in 1999 and reached its minimum in May, 2000, five months before the mainshock. The biggest deviation from the background level is about 19σ. A recovery stage from the quiescence pattern to the background seismicity followed. The positive anomaly in late 1997 would be due to the earthquake swarm that occurred between August 23 and December 31, 1997 (Huang and Nagao 2002).

I also investigated the spatial distribution of seismic quiescence quantified by the Q - parameter, which is introduced in Section 2.2. Figure 5 shows the Q - map from December, 1998 to May, 1999, when a significant quiescence stage was revealed by the RTL value (Fig. 4). The seismic quiescence of the 2000 Tottori earthquake appeared in a broad area around the epicenter. The maximum linear size of this anomalous zone (Q - parameter) is about 200 km (also see Table 1), several times larger than the rupture length of the mainshock, which is of the order of several tens of kilometers.

3.2.2 Kobe Earthquake (*M* = 7.2, January 17, 1995)

I calculated the temporal variations of the RTL parameter at the epicenter of the $M = 7.2$ Kobe earthquake based on the earthquakes in the circular zone with a radius of $R_{\max}$ in the JMA catalog (1977 - 1995). The spatial distributions of seismic quiescence and activation were also investigated using the methods introduced in Section 2.

Figure 6 shows the temporal variation of the RTL parameter at (135.04°E, 34.59°N) the epicenter of the Kobe earthquake. This RTL curve is obtained on the basis of the RTL algorithm, which was introduced in Section 2.1. All events used in the above calculations satisfy the following criteria: magnitude $M_i \geq 3.0$, focal depth $d_i \leq 100$ km, epicentral distance $r_i \leq R_{\max} = 100$ km, and time interval $(t - t_i) \leq T_{\max} = 2$ years. An obvious seismic quiescence was obtained from this RTL curve, followed by an activation stage. The quiescence started in 1993 and reached its bottom one year later. The biggest deviation from the background was about 7σ. The temporal variations of three functions, R(135.04°E, 34.59°N, 0, t), T(135.04°E, 34.59°N, 0, t), and L(135.04°E, 34.59°N, 0, t) are also shown in Fig. 6 with grey lines. These three functions deviate consistently from their background levels in 1994. It should be also

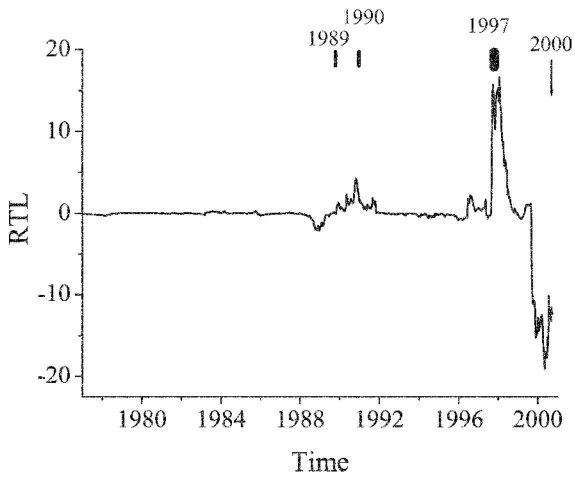

Fig. 4. Temporal variation of the RTL parameter (in unit of the standard deviation, σ) at the epicenter of the 2000 Tottori earthquake. A significant quiescence stage appeared between 1999 and 2000. The arrow shows the occurrence time of the Tottori event. The bold lines indicate the time interval of swarms in 1989, 1990, and 1997, respectively.

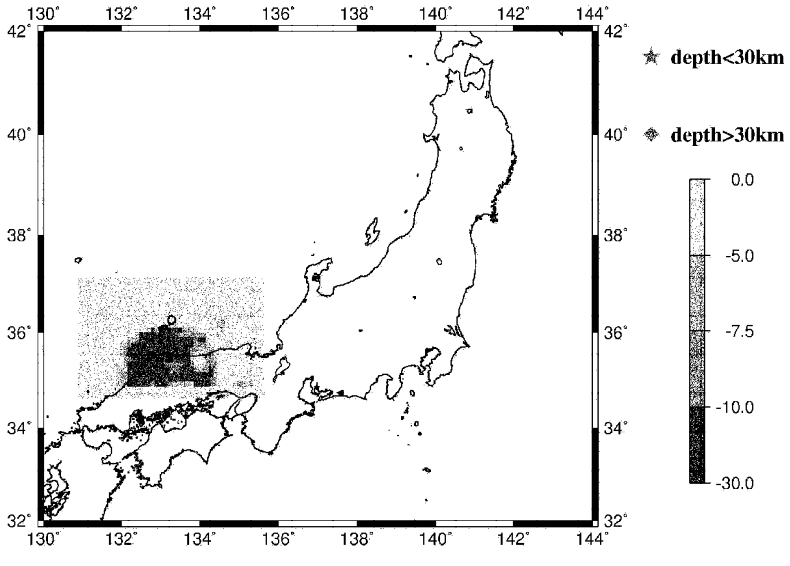

Fig. 5. Spatial distribution of seismic quiescence quantified by the Q-parameter (in unit of the standard deviation, σ) from December, 1998 to May, 1999. The star indicates the epicenter of the M = 7.3 Tottori earthquake on October 6, 2000.

mentioned that another clear quiescence was detected in 1984, which will be discussed in Section 4.1.

I calculated the quiescence distribution between May 11, 1993 and May 10, 1994, because a significant quiescence stage was revealed during this period by the RTL parameter (Fig. 6). An anomaly of quiescence appeared around the epicenter of the Kobe earthquake (see details in Huang et al. 2001). The linear dimension of this anomalous zone was about 300 km (Table 1).

Figure 7 shows the spatial distribution of seismic activation based on the S - parameter [Eq. (4) in Section 2.3] during an interval of seven months from May to December 1994, because an activation stage was detected during this period by the RTL parameter (Fig. 6). An anomalous zone (*S* - parameter) of seismic activation of the order of several tens of kilometers was obtained around the epicenter of the Kobe earthquake (see details in Huang et al. 2001).

3.3 Earthquakes in Turkey

The RTL algorithm was applied to investigate the seismicity patterns associated with the $M_w = 7.4$ Izmit (Turkey) earthquake, August 17, 1999, based on local (Izmit tectonic zone)

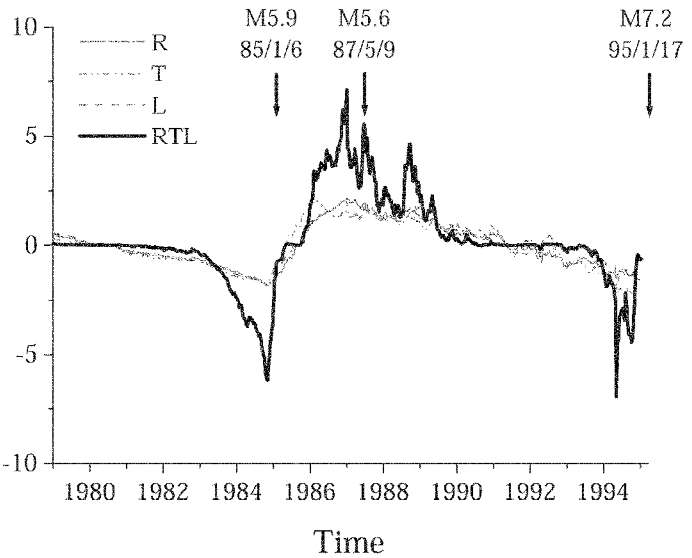

Fig. 6. The temporal variation of the RTL parameter (in unit of the standard deviation, σ) at (135.04°E, 34.59°N) the epicenter of the 1995 Kobe earthquake. This curve is obtained by changing the calculated time at a step of 10 days. A significant quiescence appeared in 1993, followed by an activation stage. Arrows indicate the occurrence time of earthquakes. The $M = 5.9$ earthquake occurred on January 6, 1985 and the $M = 5.6$ earthquake occurred on May 9, 1987.

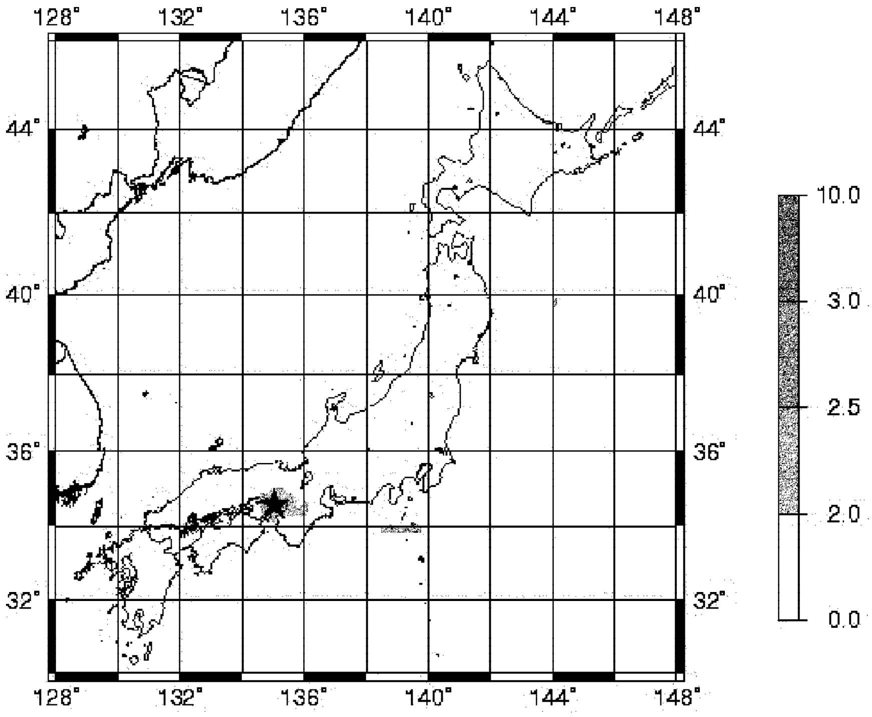

Fig. 7. Spatial distribution of seismic activation from May to December 1994. The epicenter of the Kobe earthquake (black star) located almost in the center of this anomalous zone, which is in order of several tens of kilometers. The scale bar is in arbitrary unit.

and national (Turkey) earthquake catalogs. These two catalogs were compiled from the raw catalog (1981 - 1999) of the Kandilli Observatory and Earthquake Research Institute, Bosphorus University (KOERI) by declustering aftershocks (see Huang et al. 2002).

The rupture dimension, l_i for earthquakes in Turkey was given by an empirical relation with magnitude, *M* (Toksöz et al. 1979),

$$\log l_i(\text{km}) = 0.78M_i - 3.62, \tag{7}$$

and this relation is used to determine *li* for earthquakes in the present study.

Figure 8 gives the temporal variation of the RTL parameter at the epicenter of the 1999 Izmit earthquake. The solid curve was calculated from the national catalog and the dashed one was calculated from the local Izmit catalog. The quiescence, revealed by the RTL parameter, started at the end of 1995 and reached its minimum in December, 1996. The greatest deviation from the background exceeds 6σ for the national catalog and 10σ for the local Izmit catalog.

An activation stage with a duration of about three months followed.

The spatial distribution of the seismic quiescence quantified by the Q - parameter shows that a clear quiescence anomaly appeared around the epicenter of the Izmit earthquake during the period from July 1, 1996 to December 31, 1996. The maximum linear dimension of this anomalous zone reached 150 km (Table 1, also see Huang et al. 2002).

3.4 Earthquake Swarms

Because my previous works (Huang and Nagao 2002; Huang et al. 2002) indicated that the positive RTL anomaly may be due to clustered earthquakes or increased seismicity, I also investigated the seismicity changes of earthquake swarms with respect to a long-term background in the Izu Island region of Japan by applying the RTL algorithm to the JMA earthquake catalog. After eliminating aftershocks from the earthquake data using the algorithm developed by Molchan and Dmitrieva (1992) and estimating the completeness of this catalog based on the power law of frequency-magnitude (Smirnov 1998), I chose the background from January 1, 1977 to July 1, 2000 and the cut-off magnitude $M_{\min} = 3.0$ for the JMA catalog in the

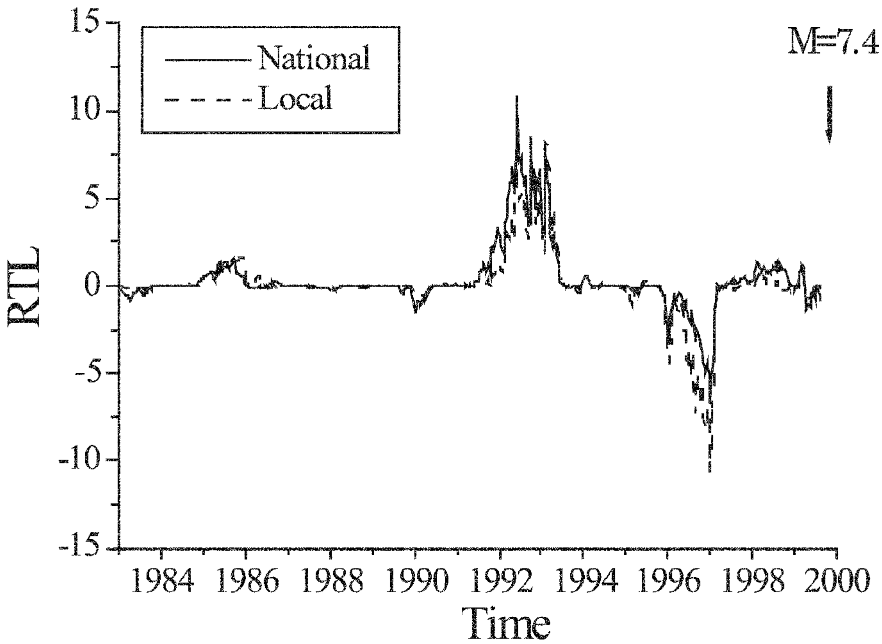

Fig. 8. Temporal variation of the RTL parameter (in unit of the standard deviation, σ) at the epicenter of the $M_w = 7.4$ Izmit earthquake (August 17, 1999), calculated from the national (Turkey) and the local (the total rupture zone of the Izmit earthquake and the $M_w = 7.2$ Duzce event (November 12, 1999) earthquake catalogs. The arrow indicates the occurrence time of the mainshock.

investigated region (with longitude between 135.5°E - 140.0°E and latitude between 33.5°N - 38.0°N) of central Japan. Figure 9 gives the temporal variation of RTL parameters at the epicenter (139.22°E, 34.20°N) of the largest event (*M* = 6.4, July 1, 2000) of the 2000 Izu earthquake swarm. A quiescence pattern started around 1999. The biggest deviation from the background level occurred in June 1999 and is 6.35σ. The duration of this anomaly is 1.4 years (Table 1). The seismicity was lower than the background level until the end of June. However, it increased suddenly and was much higher than the background level when the *M* = 6.4 event occurred on July 1, 2000 (Fig. 9). As mentioned previously, a positive RTL parameter means that the seismicity is higher than the background level. So the positive RTL changes in 1997 and in June 2000 indicated the high seismic activity in the Izu Island region. These positive anomalies would be due to the preparation and occurrence of the earthquake swarms in 1997 and 2000.

I also adopted the *Q* - parameter, which is defined by Eq. (2) in Section 2.2, to quantify the seismic quiescence at a certain position. After changing the calculated position at a step of 0.1° respectively along longitude and latitude in the investigated region of central Japan, one can obtain the spatial distribution of seismicity quiescence quantified by the *Q* - parameter. I will only summarize the main results here and discuss the details in a separate paper elsewhere

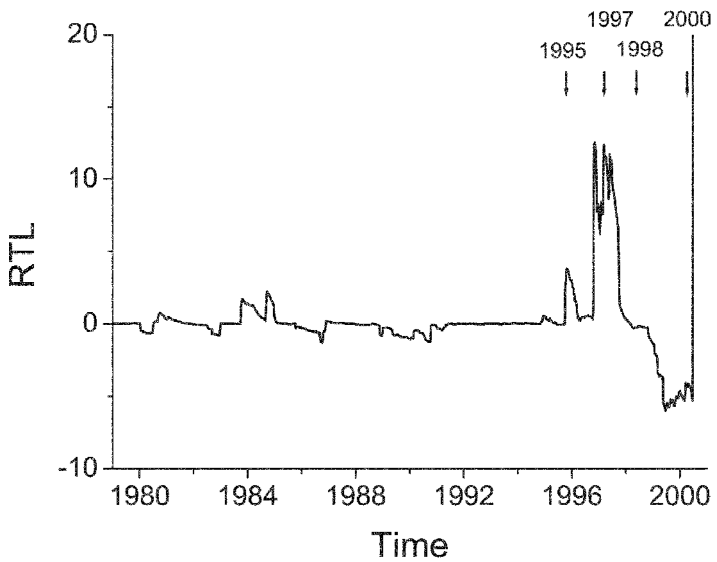

Fig. 9. Temporal change of the seismicity around the epicenter (139.22°E, 34.20°N) of the largest event (*M* = 6.4, July 1, 2000) of the 2000 earthquake swarms in the Izu Island region. The RTL parameter is in unit of the standard deviation, σ. The arrows indicate the earthquake swarms occurred in the Izu Island region between 1995 and 2000.

(Huang 2004). A clear anomalous quiescence zone appeared around the Izu Island region between January and June 1999. A similar anomalous quiescence zone was recognized between July and December 1999, but became weak from January to June 2000 and tended to disappear between July and December 2000.

4. DISCUSSIONS

4.1 Artificial Anomalies due to Changes in a Seismological Network

What I am concerned with is the seismicity anomaly associated with the preparation of earthquakes. However, seismicity changes may be also be caused by some artificial effects, e. g., either due to changes in seismological networks (Habermann 1987, 1991) or due to the selection of model parameters. In order to differentiate between real and the artificial possibilities for RTL anomlies, I will take the Kobe earthquake as an example and evaluate the quality of the JMA earthquake data in this section and discuss the possible influences of the selection of model parameters in Section 4.2.

I investigated the temporal variations of the earthquake number in the study zone ($r_i \le R_{max} = 100$ km). A total of 14825 events occurred in the study zone from 1977 to 1995. The histogram of yearly number and the diagram of cumulative number indicate that there are significant increases in earthquake numbers around 1984 and between 1993 and 1995 (Huang et al. 2001). These increases may be due to changes in JMA's seismological network. In fact, the JMA network has undergone many changes not only in instrumentation, but also in data management. Some major changes in the nation-wide JMA network until 1990 were discussed by Ohtake and Ishikawa (1995). The JMA improved the accuracy of locating focal depth, longitude and latitude in October 1983. The JMA network of the Osaka local center (including the Kobe region) introduced a new system of L/ADESS (local automated data editing and switching system) in 1984. The above changes in data observation and processing systems of the JMA Osaka local center would explain the sudden increase of earthquake number around 1984. Besides the above changes, the ETOS (earthquake and tsunami observation system) was introduced in the JMA stations of the Osaka local center in 1993, and the temporary tsunami observation network was in operation from October 1994 to early 1995. The significant increase in earthquake numbers from 1993 to 1995 may be associated with the above changes in the JMA network of the Osaka local center.

After following the aftershock elimination procedure, 5056 events (about 34% of total events) were identified as aftershocks and thus eliminated from the catalog. For comparison, Figs. 10a, b give diagrams of the cumulative number with $M_i \ge 3.0$ before and after the application of the aftershock elimination algorithm. After comparing the variation of the cumulative number, I found that the influence due to changes in the JMA seismological network in 1993 through 1995 can be reduced significantly after introducing a cut-off magnitude $M_{min} = 3.0$ and eliminating aftershocks from the earthquake catalog. Therefore, the quiescence anomaly in 1994 (Fig. 6), which was revealed by the RTL algorithm, would have reasonable correlation with the preparation of the $M = 7.2$ Kobe earthquake. It should also be mentioned that another significant RTL anomaly was detected in 1984, and two moderate earthquakes occurred in the study zone. Although there is a possibility that the anomaly in 1984 is associated with the events that followed, it is also possible that this anomaly is an artificial effect due to the changes of the JMA seismological network (Fig. 10).

4.2 Artificial Anomalies due to the Selection of Model Parameters in the RTL Algorithm

As mentioned in previous studies, the selections of some model parameters (criteria for earthquakes) in the RTL algorithm are somewhat empirical and arbitrary. Therefore, it is ap-

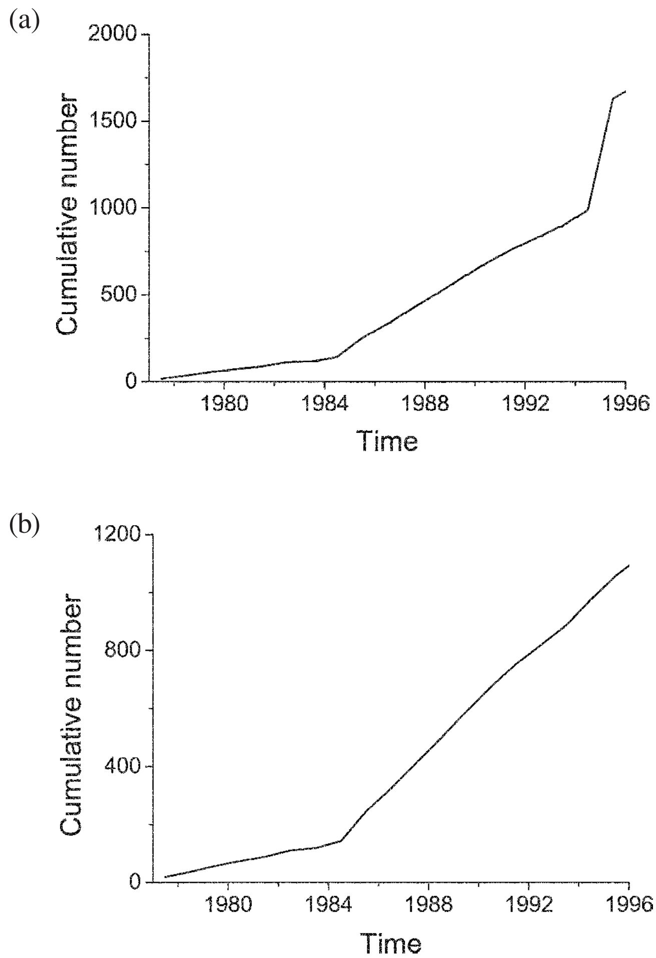

Fig. 10. The temporal variation of the number of earthquakes during the period from 1977 to 1995 satisfying $M \geq 3.0$ in a circular zone within 100 km of the epicenter of the 1995 Kobe earthquake. (a) Before eliminating aftershocks; (b) after eliminating aftershocks.

propriate to investigate whether or not the results are artifacts due to the selections of the above model parameters. For this purpose, I repeated the calculations changing these parameters and calculated the correlation coefficient between the results obtained from different model parameters.

As an example, I will summarize the results of the Kobe earthquake (Huang et al. 2001). The following model parameters were chosen in calculating Fig. 6: cut-off depth $d_0 = 100$ km, $r_0 = 50$ km ($R_{max} = 2r_0 = 100$ km) and $t_0 = 1$ year ($T_{max} = 2t_0 = 2$ year). The re-calculation after changing the model parameters leads to quite similar results as shown in Fig. 6. Table 2 gives the correlation of RTL values between different model parameters. Significant correlation was proved by the statistical test for the above cases at a significance level of 0.05 (Bendat and Piersol 2000). Thus, the above investigations indicated that the variations of the model parameters do not have much influence on the results, i.e., the seismicity changes of the Kobe earthquake revealed by the RTL algorithm are not artifacts due to the selections of the model parameters.

Similar conclusion holds for other earthquakes (e.g., Huang and Nagao 2002; Huang and Sobolev 2002; Huang et al. 2002).

4.3 Significance of an Anomaly

Besides the analysis of the temporal and spatial changes of seismicity patterns, the significance of the anomaly was also investigated using a stochastic test (Huang et al. 2002; Sobolev et al. 2002).

Table 2. Correlation of RTL values between different model parameters ($R_{max} = 2r_0$ and $T_{max} = 2t_0$)

Cases	**A**	$d_0 = 100$ km, $r_0 = 50$ km, $t_0 = 1$ year					
	B	$d_0 = 999$ km $r_0 = 50$ km $t_0 = 1$ year	$d_0 = 30$ km $r_0 = 50$ km $t_0 = 1$ year	$d_0 = 100$ km $r_0 = 25$ km $t_0 = 1$ year	$d_0 = 100$ km $r_0 = 75$ km $t_0 = 1$ year	$d_0 = 100$ km $r_0 = 50$ km $t_0 = 0.5$ year	$d_0 = 100$ km $r_0 = 50$ km $t_0 = 1.5$ years
Correlation coefficient		0.960	0.926	0.861	0.981	0.632	0.731

Figure 11 shows the principle of the stochastic test. First, random earthquake catalogs were generated by randomizing the time and space (longitude and latitude) of the seismological catalog. Then, for each random catalog, the RTL parameter was calculated at the epicenter of the investigated earthquake. I chose the same criteria as were used in the calculations for the real catalog. After quantifying the negative anomaly of the RTL parameter, one can estimate whether an RTL anomaly appears or not. Finally, one can calculate the RTL parameters at the epicenter for many (e.g., $n = 1000$) random catalogs and estimate the probability of occurrence of an RTL anomaly. As an example of the $M = 7.3$ Tottori earthquake, the chance probabilities of the observed RTL anomalies before the mainshock (Fig. 4) are less than 0.01 (taking $n = 1000$). Thus, I concluded that the RTL anomaly, which was obtained before the Tottori earthquake (Fig. 4), is unlikely to be a chance anomaly, so it is significant. Similar conclusions also hold for some other cases (e.g., Huang et a. 2002; Sobolev et al. 2002).

4.4 General Characteristics and Potential Applications of Seismicity Changes

The temporal variation of the seismicity patterns showed similar characteristics before strong earthquakes in Russia (Sobolev and Tyupkin 1997, 1999), Japan (Huang and Sobolev 2001, 2002; Huang and Nagao 2002; Huang et al. 2001) and Turkey (Huang et al. 2002). The seismic quiescence pattern started a few years before the mainshock and lasted from 1 to 2.5

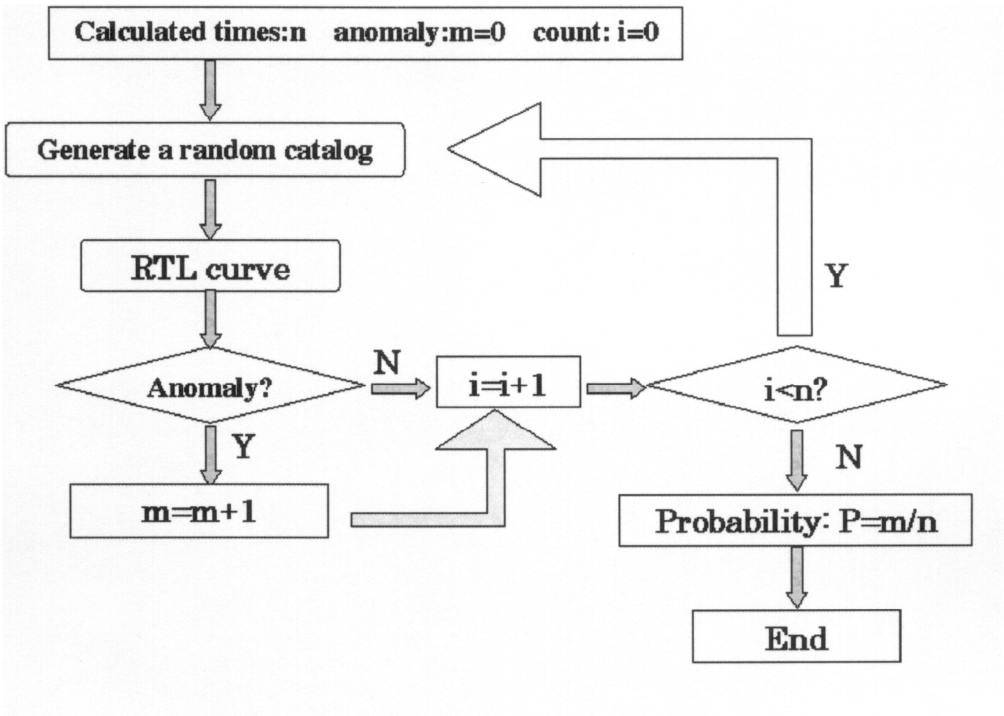

Fig. 11. A sketch of the stochastic test for the seismicity anomaly revealed by the RTL algorithm.

years. The duration of the subsequent pattern of seismic activation generally lasted several months. The dimension of the quiescence zone reached a few hundred kilometers (several times the rupture dimension of the mainshock), while the activation zone was generally in order of several tens of kilometers (comparable to the rupture dimension) (Table 1). The similarity in these variations of seismicity patterns prior to strong earthquakes in different tectonic regions may reflect the natural evolution of the seismogenic process. Thus, the RTL algorithm is an effective tool for revealing seismicity pattern changes before strong earthquakes.

It seems reasonable to suppose that an earthquake is most likely to occur once the relevant source region has passed through the quiescence and activation stages. Variations in seismicity patterns may provide information useful for earthquake alert. Detailed investigation of spatial changes of seismic quiescence anomalies after combining the temporal variations of seismicity patterns at different positions would be useful for seismic hazard assessment.

It should be mentioned that the intermediate - term prediction on the basis of the RTL algorithm would be possible when a routine earthquake catalog becomes available. The first test in Kamchatka showed that the quiescence pattern started in mid - 1995, reached the minimum RTL value by the end of 1995, and was followed by a foreshock activation pattern (Sobolev and Tyupkin 1999). Based on this analysis, a message was sent to the Earthquake Prediction Expert Council, Ministry of Emergency Situation, Russia, and the leaders of the Geophysical Service, Russian Academy of Sciences, on August 7, 1996. It reported that a quiescence anomaly centered in the Gulf of Kamchatka was an intermediate - term precursor of an earthquake with $M \geq 7$. In fact, an earthquake with $M = 7.7$ occurred on December 5, 1997 within the anomalous zone of quiescence (Sobolev and Tyupkin 1999).

Besides its application in risk alarm of strong earthquakes, the RTL algorithm would also be useful for risk alarming of large earthquake swarms. The study on earthquake swarms in the Izu Island region showed that the increase in the normalized RTL parameter seems to have some correlation with the earthquake swarms (arrows in Fig. 9) that occurred from 1995 to 2000. The largest increase in the RTL parameter (except that of the 2000 swarm) appeared before and during the 1997 earthquake swarm, which is the largest swarm to have occurred within several years of the 2000 swarm. The 1997 swarm has a higher weight than other previous swarms (e.g., the 1995 swarm); the larger positive RTL in 1997 may reflect the greater number of contributions of the 1997 swarm. Because a positive RTL means high seismicity with respect to background level and close analysis indicated that the change of JMA's seismological system around October 1997 did not cause man - made change of accelerated seismicity (Huang 2004), the anomaly in 1997 may be due to the activation stage of the preparation and occurrence of the 1997 swarm. It should be mentioned that because most events of the 2000 earthquake swarm occurred very close to the place 139.22°E, 34.20°N where the RTL parameters were calculated, the results would reflect the characteristics of the whole earthquake swarm, rather than those of a certain event. Of course, in order to obtain more reliable results, one should make close investigation of both the temporal seismicity variations at a certain place revealed by the RTL parameter and the spatial distribution of seismicity changes quantified by the Q - parameter, just as has been done in my study. Thus, the increased RTL parameter would become a potentially useful new index for risk alarm of earthquake swarms.

5. CONCLUSIONS

The RTL algorithm and the related parameters were applied to earthquake data in various tectonic regions. Case studies for large earthquakes in Russia, Japan and Turkey indicated that seismic quiescence and activation stages occurred in the rupture regions. The temporal changes and the spatial distributions revealed consistent characteristics in seismicity pattern changes. The seismic quiescence anomalies generally started a few years before the occurrence of the earthquakes and lasted from 1 to 2.5 years. The duration of the subsequent seismic activation generally lasted several months. The linear dimension of the quiescence zone reached a few hundred kilometers, while the activation zone was generally in order of several tens of kilometers. To distinguish real seismicity pattern changes from the possible artificial effects, I analysed the influence of both changes in seismological networks and selection of model parameters in the RTL algorithm. I concluded that all the anomalous changes before large earthquakes or swarms revealed in our works are unlikely due to the above artificial effects. I also did a stochastic test for the revealed anomalies and proved their significance. Besides the potential application in risk alarm of large earthquakes, the RTL algorithm and the related parameters were also applied to the study of earthquake swarms. The case study for the swarms in the Izu Island region indicated that the increased RTL parameter would become a potentially useful new index for risk alarm of earthquake swarms.

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