Available online at www.sciencedirect.com
SCIENCE DIRECT®
ELSEVIER
Journal of Asian Earth Sciences 26 (2006) 509–517
Journal of Asian Earth Sciences
www.elsevier.com/locate/jaes

Seismicity changes associated with the 2000 earthquake swarm in the Izu Island region

Qinghua Huang*

Computational Geodynamics Laboratory, Department of Geophysics, Peking University, Beijing 100871, China

Received 30 January 2004; revised 14 July 2004; accepted 1 November 2004

Abstract

A statistical method taking into account the information of magnitude, occurrence time and location of earthquakes was applied to the earthquake data (1977–2000) of the Japan Meteorological Agency (JMA) to investigate seismicity changes in the Izu Island region. The analysis indicated that a quiescence anomaly started about 1.5 years before the occurrence of the largest swarm in the summer of 2000 in the Izu Island region. Close investigations of the possible artifacts due to the selection of model parameters and the improvement of the seismological network lead to the conclusion that the above quiescence anomaly is unlikely a man-made change. The further stochastic test using 1000 random earthquake catalogs supports the idea that the above anomaly is significant. The spatial distribution of the seismic quiescence, which is quantified by a newly developed Q-parameter, revealed a clear anomalous region around the epicentral area of the above earthquake swarm. The seismicity revealed by the normalized parameter tends to increase just before the swarm. As the first test of the above statistical method for investigating seismicity changes of earthquake swarms, this study indicates that the increased *RTL* parameter would be a new potentially useful index for the risk alarm of earthquake swarms.

Keywords: Earthquake swarm; Seismicity changes; Seismic quiescence; Accelerated seismicity; Izu Island region

1. Introduction

The Izu Island region (Fig. 1) is a seismic and volcanic active zone in central Japan. Table 1 gives the main earthquake swarms that have occurred in this region since 1979. The earthquake data are from the Japan Meteorological Agency (JMA) and the energy is estimated using the empirical relation $\log E = 1.5M + 4.8$, where E is the energy in units of J and M is the magnitude of an earthquake in the Izu Island region (Fig. 1). Table 1 shows that the earthquake swarm that occurred in the summer of 2000 is the largest one since 1979. According to the JMA data and other temporary observations by Tokyo University, the number of events that occurred during the 2000 earthquake swarm were even more than those of the past 5.5 years.

The question of whether or not an earthquake can be predicted is highly controversial. Some scientists continue to find valuable earthquake precursors, e.g. electromagnetic signals (Nagao et al., 2002; Uyeda et al., 2002), seismicity changes (Kossobokov and Keilis-Borok, 1990; Wyss and Martirosyan, 1998; Wyss and Matsumura, 2002; Öncel and Wyss, 2000; Öncel and Wilson, 2002; Öncel et al., 1996), etc. Because seismicity precursor has been tested for a long period of time and some positive examples have been obtained (Sobolev and Tyupkin, 1997, 1999; Sobolev et al., 2002; Huang and Nagao, 2002), seismicity analysis continues to play an important role in earthquake prediction. Some recent studies indicate that one statistical method, which is called the *RTL* (Region–Time–Length) algorithm (Sobolev and Tyupkin, 1997), is a useful tool in revealing the seismicity precursor for strong earthquakes (Di Giovambattista and Tyupkin, 2001; Huang and Sobolev, 2002; Huang et al., 2001, 2002; Huang, 2004). However, this method has not been tested for earthquake swarms. It should be mentioned that some other approach (e.g. time-to-failure analysis) has been used for estimating the occurrence time of volcanic activity (Main, 1999).

* Corresponding author. Fax: +86 10 6276 8894.
E-mail address: huangq@pku.edu.cn.

1367-9120/$ - see front matter © 2004 Elsevier Ltd. All rights reserved.
doi:10.1016/j.jseaes.2004.11.005

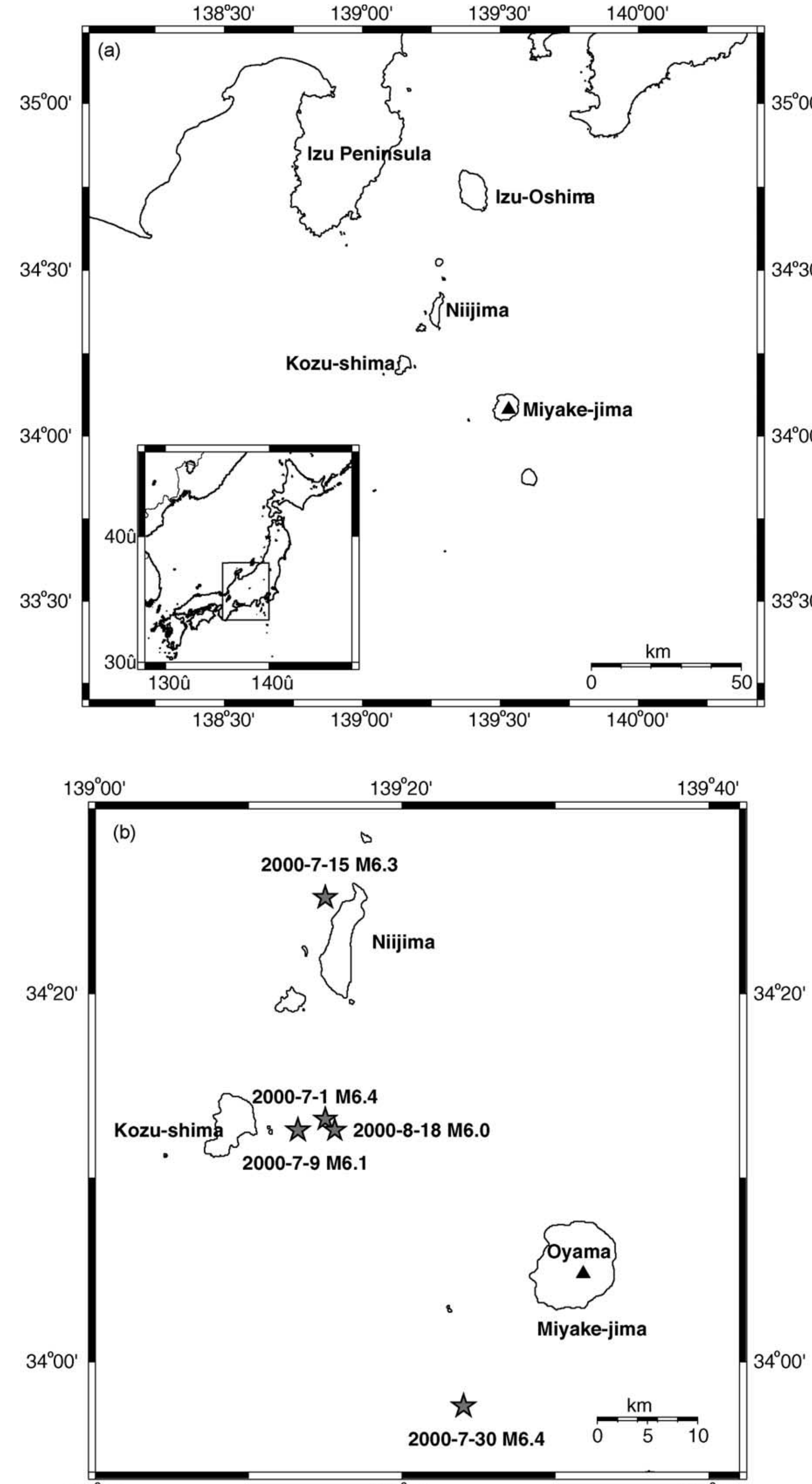

Fig. 1. Map of the Izu region. (a) The lower left shows the map of Japan, where the rectangle is the investigated region (latitude between 33.5 and 38.0°N and longitude between 135.5 and 140.0°E) in this study. The black triangle represents the volcano Oyama, Miyakejima Island. (b) The enlarged map of the Izu Island region. The gray stars are the $M \geq 6.0$ events during the 2000 earthquake swarm.

Table 1
List of the earthquake swarms in the Izu Island region

Interval	Total energy[a] (J)
1980/06/23–1980/10/01	7.3×10^{14}
1983/01/14–1983/02/25	1.2×10^{12}
1984/08/30–1984/10/11	1.4×10^{12}
1988/07/26–1988/09/15	1.9×10^{13}
1989/06/30–1989/09/06	2.4×10^{13}
1993/05/26–1993/06/15	2.3×10^{12}
1995/09/29–1995/10/28	2.1×10^{12}
1997/03/03–1997/03/26	3.0×10^{13}
1998/04/20–1998/06/02	2.6×10^{13}
2000/06/26–2000/08/31	1.2×10^{15}

[a] Energy is estimated by the empirical relation $\log E = 1.5M + 4.8$, where E is in unit of J and M is the magnitude of an earthquake in the Izu Island region.

In this paper, I will report on the seismicity changes in the Izu Island region. The earthquake data of JMA were chosen for this study. I will make a first attempt to apply the *RTL* algorithm and the newly developed *Q*-parameter (Huang et al., 2002) to the investigation of seismicity changes associated with earthquake swarms.

2. The 2000 earthquake swarm

On June 26, 2000, an official alarm was issued for imminent volcanic activity of Oyama Volcano (the black triangle in Fig. 1(b)), Miyake-jima Island by the JMA. This alarm was based on the increased occurrence of small earthquakes under the island. The next morning, several kilometers west of the island, there was indication of an undersea eruption, and the seismic swarm activity started almost simultaneously.

There were five earthquakes of $M \geq 6.0$ (among which were two earthquakes of $M = 6.4$) in the 2000 swarm (Fig. 1(b)). According to the JMA's report (Japan Meteorological Agency, 2000), at the first stage of this swarm (June 26–July 1), earthquake epicenters first migrated westward (about 5–10 km) from the Miyake-jima island and then northwestward (about 20–30 km) (Fig. 2). The largest $M = 6.4$ earthquake occurred on July 1, at the end of the first stage of the swarm. During the coming stages, earthquake activity continued in the area between Kozu-shima and Miyake-jima; a large-scale depression at the summit of the volcano occurred on July 8; an additional four events of $M \geq 6.0$ occurred on July 9 ($M = 6.1$), July 15 ($M = 6.3$), July 30 ($M = 6.4$), and August 18 ($M = 6.0$), respectively (Fig. 1(b)); and the largest eruption of the Oyama Volcano occurred on August 18. The last major volcanic eruption was on August 29, 2000. This eruption continued for about two hours and the dark-colored eruption cloud rose about four kilometers above the summit caldera.

3. Methods

The *RTL* algorithm (Sobolev and Tyupkin, 1997; Huang et al., 2001) takes into account the weighted quantities associated with all three parameters (time, place and magnitude) of earthquakes. The weight becomes greater when the earthquake is larger in magnitude or is closer to the investigated place or time. The *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,

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

where l_i is the rupture dimension (a function of magnitude M_i, given by the empirical relation $\log l_i\,(\text{km}) = 0.5\,M_i - 1.8$ (Kasahara, 1981)), t_i the occurrence time of the ith 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. $M_i \geq M_{\min}$ (M_i is the magnitude of the ith earthquake and $M_{\min}$ is the cut-off magnitude ensuring the completeness of the earthquake catalog), $r_i \leq R_{\max} = 2r_0$ and $(t - t_i) \leq T_{\max} = 2t_0$; $R_{bk}(x, y, z, t)$, $T_{bk}(x, y, z, t)$ 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, $\sigma = \sigma_R \sigma_T \sigma_L$. 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.

I also employed 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), 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,

$$Q(x,y,z,t1,t2) = \frac{1}{m} \sum_{i=1}^{m} RTL(x,y,z,ti), \qquad (2)$$

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

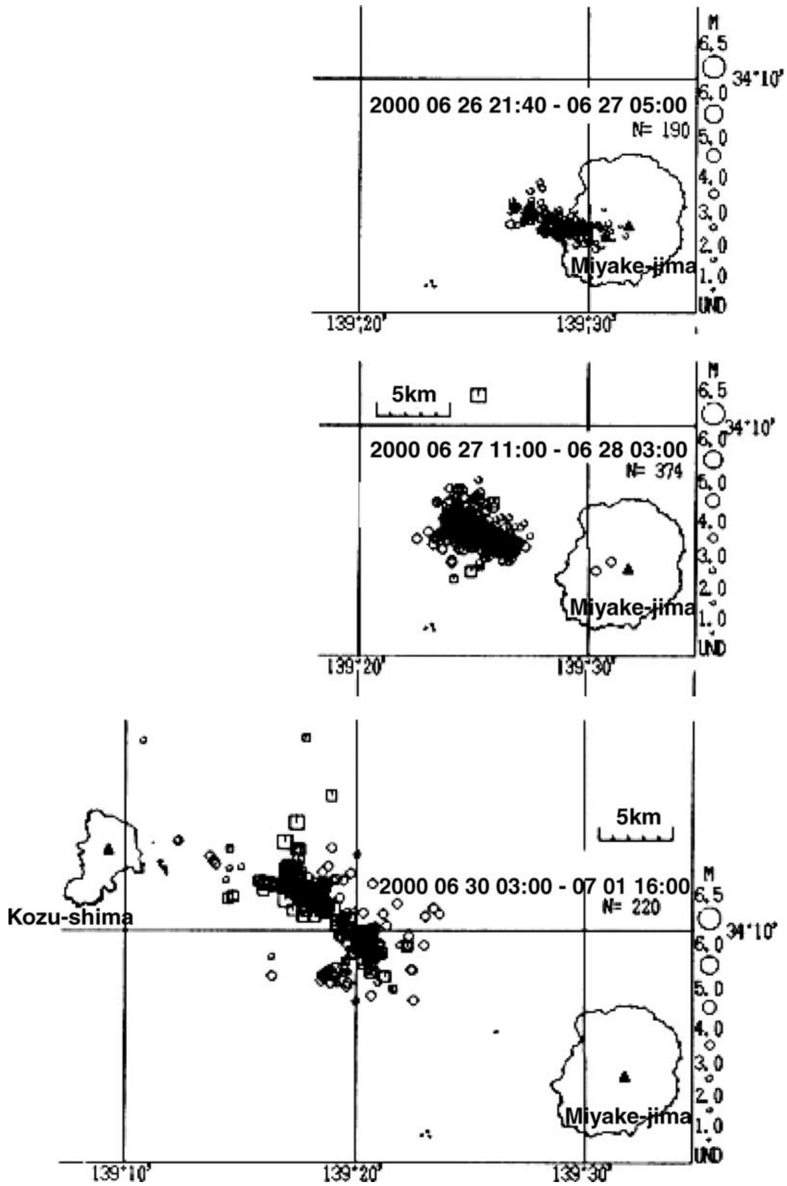

Fig. 2. Migration of earthquakes during the first stage (June 26–July 1) of the 2000 swarm in the Izu Island region (modified after Fig. 2(a) of Japan Meteorological Agency, 2000).

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.

4. Seismicity changes

I investigated the seismicity changes with respect to a long-term background in the Izu Island region by applying the *RTL* algorithm to the JMA earthquake catalog. Because the manual operation of data in the JMA earthquake catalog was replaced by the computer operation in 1961, the earthquake catalog since 1961 was chosen in this study. Before applying the *RTL* algorithm, I eliminated aftershocks from the JMA earthquake catalog using the algorithm developed by Molchan and Dmitrieva (1992) and estimated the completeness of this catalog based on the power law of frequency-magnitude.

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. In order to compare the difference before and after the procedure of aftershock elimination, I investigated

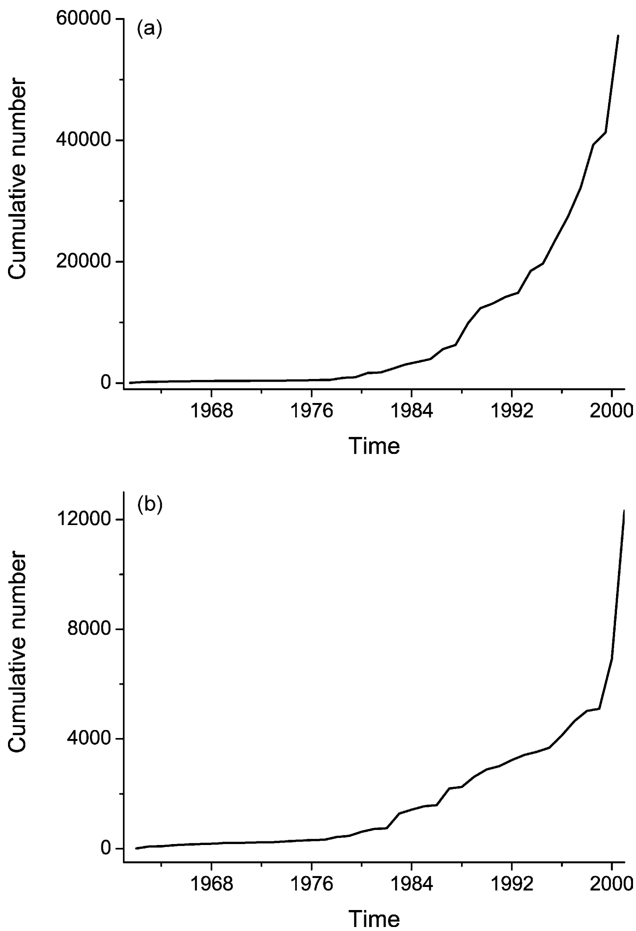

Fig. 3. Temporal changes of the cumulative number of earthquakes from the original JMA earthquake catalog in a circular zone within 100 km of the epicenter (139.22°E, 34.20°N) of the $M=6.4$ earthquake occurred on July 1, 2000. (a) All events; (b) events with $M \geq 3.0$.

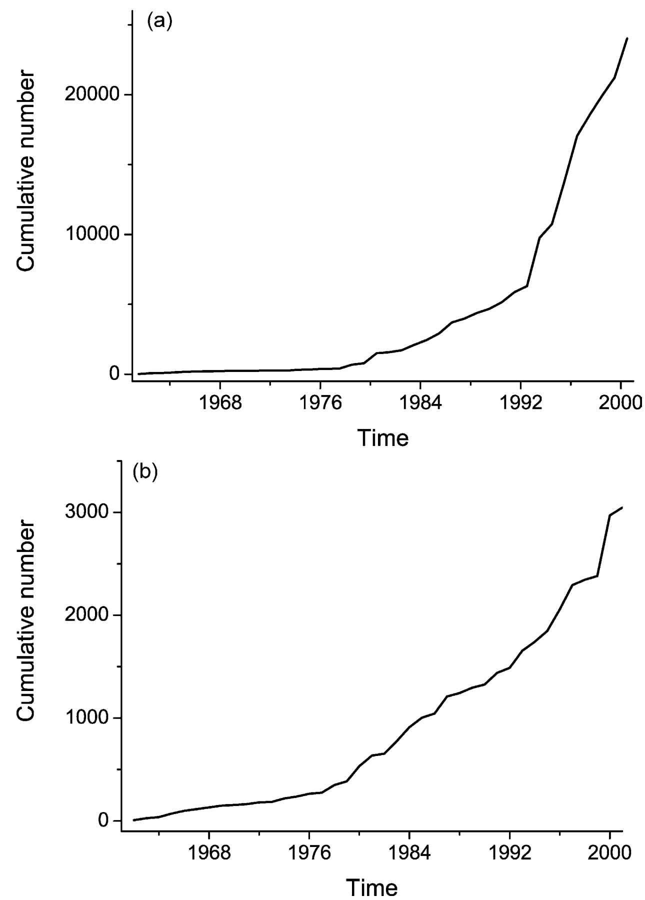

Fig. 4. Temporal changes in the cumulative number of earthquakes after the procedure of aftershock elimination in a circular zone within 100 km of the epicenter (139.22°E, 34.20°N) of the $M=6.4$ earthquake which occurred on July 1, 2000. (a) All events; (b) events with $M \geq 3.0$.

the temporal changes of seismicity in a circular zone within 100 km of the epicenter (139.22°E, 34.20°N) of the first largest event ($M=6.4$) of the 2000 Izu earthquake swarm. Fig. 3 shows the temporal changes of the cumulative number of all events (Fig. 3(a)) and the events with $M \geq 3.0$ (Fig. 3(b)) from the original JMA earthquake catalog. Fig. 4 gives the results of temporal changes of cumulative numbers after declustering aftershocks from the JMA catalog. 33,758 events (about 58% of the total events) are identified as aftershocks. It is clear that the influence due to aftershocks and the changes of the JMA seismic network can be reduced significantly (e.g. 1977–2000 in Fig. 4(b)) after eliminating aftershock and choosing a cut-off magnitude ($M_{\min}=3.0$, see next paragraph).

The pre-process of the completeness analysis using the algorithm of Smirnov (1998) showed that the cut-off magnitude, $M_{\min}=3.0$, was satisfied since 1977 for the JMA catalog in the investigated region (with longitude between 135.5°E and 140.0°E and latitude between 33.5°N and 38.0°N, see Fig. 1(a)) of central Japan. So I chose the background from January 1, 1977 to July 1, 2000, when the first largest event ($M=6.4$) of the 2000 Izu earthquake swarm occurred. I took into account only the events with $M \geq 3.0$ to ensure the completeness of the catalog. Considering that the 2000 earthquake swarm occurred in the crust, I chose only shallow events with focal depths less than 30 km as another criterion. It should be mentioned that the selection of the cut-off focal depth had little influence on the results of the current study of intermediate-term seismicity, although some other researchers paid attention to the seismicity at different parts of the crust (Öncel et al., 2001; Wyss and Matsumura, 2002). Because the *RTL* parameter is calculated based on the earthquakes in the time window $[(t-T_{\max}), t]$ and $T_{\max}=2$ years is chosen as the typical criterion in this study, it is not possible to calculate the *RTL* value for times before $t_s+T_{\max}$ (i.e. January 1, 1979), where t_s is the start time of the catalog in use.

Fig. 5 gives the temporal change of the normalized *RTL* parameter at (139.22°E, 34.20°N) using the events in the circle with a radius of 100 km (i.e. $R_{\max}=100$ km). Based on our previous experience of using the *RTL* algorithm in seismicity studies, a negative *RTL* parameter represents a lower seismicity than the background level, and given the fact that the duration of a seismic quiescence is generally larger than 0.5 years, I defined that the seismic quiescence

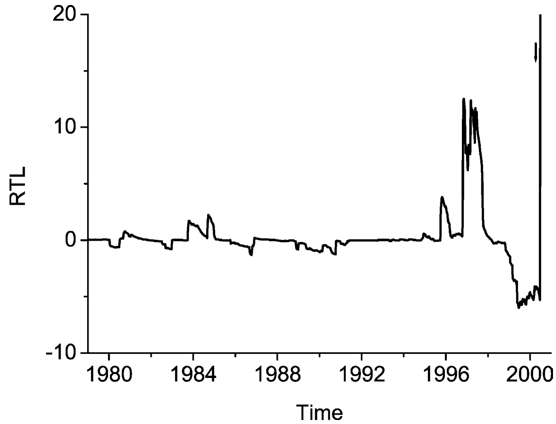

Fig. 5. Temporal change of seismicity around the epicenter of the largest event of the 2000 earthquake swarms in the Izu Island region. The $RTL=0$ represents the background seismicity around the investigated position, and the negative (positive) RTL means the seismicity is lower (higher) than the background level. The arrow indicates the earthquake swarm that occurred in the Izu Island region during the period of June–August, 2000.

anomaly in this study should satisfy the following criteria: minimum RTL parameter $\leq -5\sigma$, and duration time ≥ 0.5 year, where duration time is defined as the interval with RTL parameter $\leq -2\sigma$. A quiescence pattern started around 1999. The biggest deviation from the background level occurred in June, 1999 and is 6.35σ. The duration time of this anomaly is 1.4 years. 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. 5). As mentioned previously, a positive RTL parameter means the seismicity is higher than the background level. So the positive RTL changes in 1997 and in June, 2000 indicated high seismic activity in the Izu Island region. These positive anomalies would be due to the development and occurrence of the earthquake swarms in 1997 and 2000.

It should be mentioned that the above result (Fig. 5) gave the temporal change of seismicity at a certain position, it is also important to investigate the seismicity changes for other positions. For this purpose, I adopted the Q-parameter, which is defined by Eq. (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. The obtained Q-map is not sensitive to the selection of the calculated grid. In order to emphasize the temporal variation of the seismic quiescence, I calculated the Q-parameter in a time window of 0.5 years, although the spatial distribution of the Q-parameter is not sensitive to the selection of the time window in a reasonable range, e.g. one year. Previous studies show that the dimension of the anomalous quiescence region varies from a few to several times of the rupture length the future strong earthquake. Because the rupture length of an $M=6.4$ event is about 25 km, only the quiescence region ($Q \leq -5\sigma$) with its largest dimension over 50 km is chosen as a clear anomalous quiescence zone. Fig. 6 is the quiescence map from January to June, 1999. A clear anomalous quiescence zone appeared around the Izu Island region. A similar anomalous quiescence zone was recognized from July to December, 1999, but became weak between January and June, 2000 and tended to disappear for the period of July–December, 2000 (Fig. 7).

5. Discussion

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 appropriate 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.

I made close investigations of the possible influence of other model parameters, such as the criteria of the space (R_{max}), time (T_{max}), and so on. I obtained quite similar results as shown in Fig. 5 after changing R_{max} or T_{max}. For example, the correlation coefficients are 0.999 for $R_{max}=200$ km and 0.631 for $T_{max}=2.5$ years, respectively. 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 indicate that the variations of the model parameters do not have much influence on the results, i.e. the seismicity changes in the Izu Island region revealed by the RTL algorithm are not artifacts due to the selections of the model parameters.

Besides the selections of model parameters, the improvement of the seismological network (including changes in data processing system or algorithm) may also cause some man-made changes. In the current study, I have already introduced the cut-off magnitude M_{min} to ensure the completeness of the catalog so that the probability of artifacts due to changes in the seismological network would be minimized (e.g. Huang et al., 2001). Because the JMA has started to compile all events on the basis of a single standard since October 1, 1997, it would be useful to investigate whether or not man-made changes due to the above improvement of the JMA seismological network might be a cause of the accelerated seismicity rate. I analyzed the seismicity rate during the studied time window. Fig. 8 gives the yearly number of events of $M \geq 3.0$ within 100 km of the calculated position for the RTL curve in Fig. 5. No significant increase of seismicity was identified before or after October, 1997, judging from the event number (Fig. 8). Thus, the accelerated seismicity in 1997 revealed by the RTL algorithm (Fig. 5) is unlikely a man-made change due to change in the JMA seismological system.

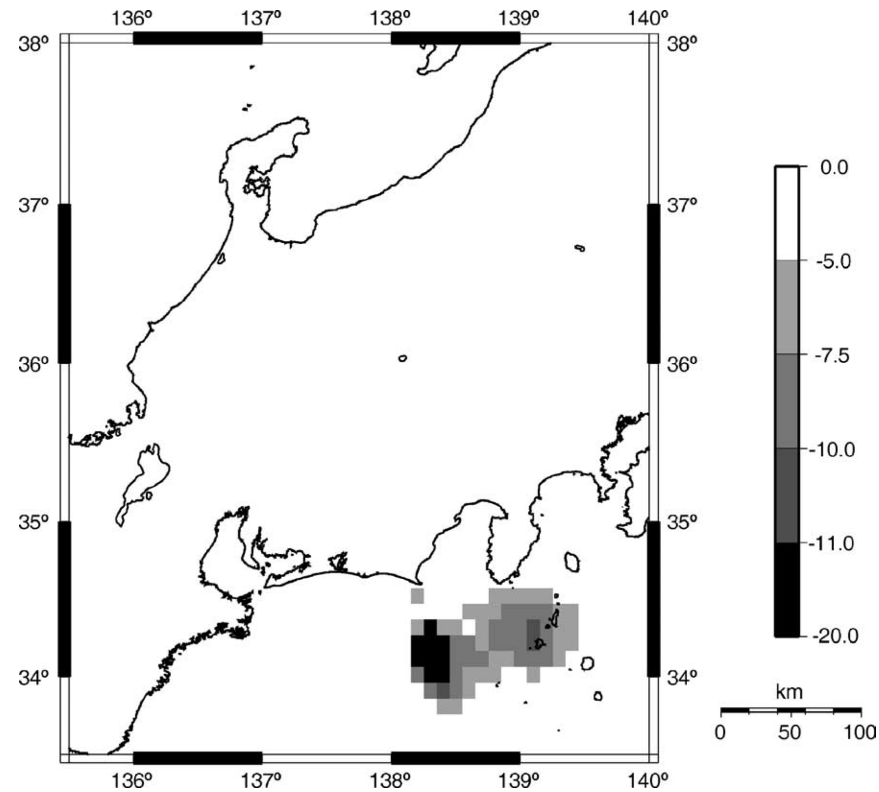

Fig. 6. Spatial distribution of the seismic quiescence in central Japan from January 1, 1999 to June 30, 1999. A clear quiescence anomaly appeared around the epicentral zone of the 2000 swarm in the Izu Island region.

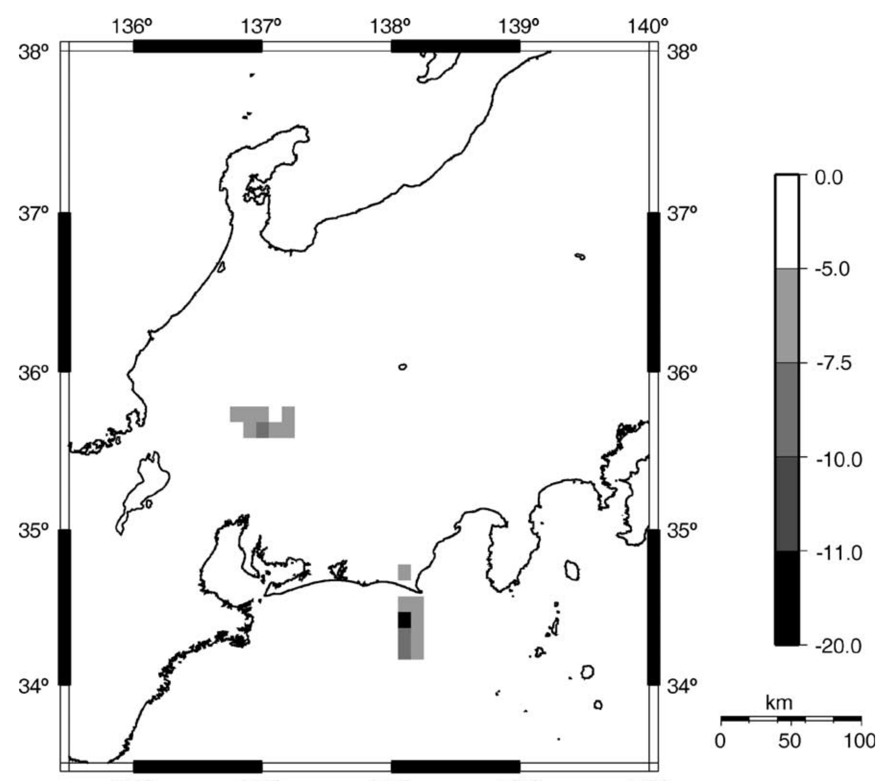

Fig. 7. Spatial distribution of the seismic quiescence in central Japan from July 1, 2000 to December 31, 2000. The anomaly in 1999 tended to disappear in the Izu Island region.

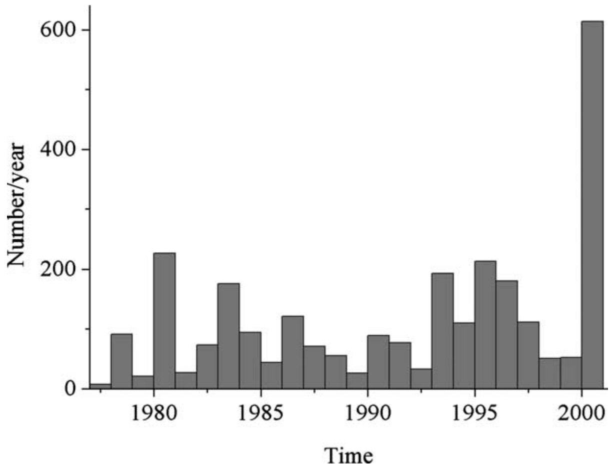

Fig. 8. Temporal change of seismicity rate after eliminating aftershocks (number/year, $M \geq 3.0$) within 100 km of the calculated position for the *RTL* curve in Fig. 5.

The statistical analysis of seismicity indicates that a clear quiescence anomaly was detected around the Izu Island region before the 2000 earthquake swarm (Figs. 3 and 4). This anomaly appeared around 1999, about 1.5 years before the 2000 earthquake swarm, but disappeared in 2000 (Fig. 7). One may find that the anomaly to the south of Omaezaki remained, although it became weaker than that appeared in 1999 (Fig. 6). Because Fig. 5 gives the temporal *RTL* curve at a certain site (the epicenter of the $M = 6.4$ earthquake on July 1) and Fig. 6 displays the spatial change during a fixed time window, the Q-parameters vary from site to site. For example, the close investigation of the Q-parameters (Fig. 6) showed that the minimum value close to the epicenters of the 2000 swarm is between $-10 \sim -11\sigma$, while that at the epicenter of the $M = 6.4$ earthquake on July 1 is -6.35σ. It should be also mentioned that a new seismic quiescence appeared around (137.0°E, 35.7°N). Although this quiescence zone is not large enough to meet the criterion of a clear quiescence anomaly, it may be interesting to monitor the temporal and spatial changes of seismicity in this region using updated earthquake data. Previous studies indicate that seismic quiescence generally appeared from 1.0 to 3.5 years before the strong earthquake. Thus, I also made the same calculation of the quiescence map quantified by the Q-parameter for some other period (e.g. for January–June, 1997, July–December, 1997, January–June, 1998, July–December, 1998, respectively) within several years of the 2000 Izu earthquake swarm, and the results indicated that no clear anomaly appeared in the investigated region. In order to investigate the significance of the quiescence anomaly revealed by the *RTL* parameter in 1999 (Fig. 5), I did a stochastic test using 1000 randomized earthquake catalogs in the investigated region of central Japan and found that the occurrence probability of the anomaly at the same level as that which was detected before the 2000 Izu earthquake swarm is 0.032. Thus, the quiescence anomaly in 1999 is significant. Because this anomaly occurred 1.5 years before the 2000 swarm around the epicentral region and the stochastic test supported its significance, it would be plausible to conclude that the above anomaly and the 2000 earthquake swarm are related.

A clear seismic quiescence appeared before the 2000 earthquake swarm (Fig. 5). However, no quiescence anomalies were ‘detected’ before the other three swarms (1995, 1997, 1998). The above difference would be due to the following reasons: (1) There is a tendency that seismicity quiescence is easier to be ‘detected’ by the *RTL* algorithm for larger earthquakes, and the 2000 swarm is the largest one among all the swarms in the Izu Island region; (2) The epicenters of the 2000 swarm are quite different (distance of about 70–80 km) from those of the other three swarms, and Fig. 5 is the temporal change of the *RTL* parameters calculated at the site among the epicenters of the 2000 swarm; (3) The *RTL* parameters reflect the total contributions from epicenter, magnitude and occurrence time of earthquakes.

Fig. 5 shows that the increase of the normalized *RTL* parameter seems to have some correlation with the earthquake swarms that occurred in the Izu Island region between 1995 and 2000. The largest increase of the *RTL* parameter (except that of the 2000 swarm) appeared before and during the 1997 earthquake swarm (Fig. 5), which is the largest swarm that occurred within several years of the 2000 swarm (Table 1). The 1997 swarm has a higher weight than other previous swarms (e.g. the 1995 swarm), and the larger positive *RTL* in 1997 may reflect the greater number of contributions of the 1997 swarm. Because the positive *RTL* means high seismicity with respect to background level, and the previous analysis indicates that the change of JMA seismological system around October, 1997 did not cause a man-made change of accelerated seismicity, the anomaly in 1997 may be due to the activation stage of the preparation and the occurrence of the 1997 swarm. It should be mentioned that because most events of the 2000 earthquake swarm occurred very close to 139.22°E, 34.20°N where I made the *RTL* calculations, 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 investigations 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 what has been done in this study. In my previous study on the 2000 $M = 7.3$ Tottori earthquake, I also found the similar phenomenon that the increased *RTL* parameter seems to have some correlation with the clustered earthquakes in the investigated region (Huang and Nagao, 2002). Thus, the increased *RTL* parameter would become a potential useful new index for risk alarm of earthquake swarms.

6. Conclusions

As the first test of the *RTL* algorithm for investigating the seismicity changes of earthquake swarms, the *RTL* algorithm was applied to the JMA earthquake data. The seismicity changes in the Izu region over a long background of between 1977 and 2000 were analyzed. A seismic quiescence appeared about 1.5 years before the 2000 earthquake swarm in the Izu Island region. The close investigations of the possible artifacts due to the selection of model parameters and the improvement of the seismological network lead to the conclusion that the above quiescence anomaly is unlikely a man-made change. The stochastic test using 1000 random earthquake catalogs indicated that the occurrance probability of the above quiescence anomaly is 0.032, indicating that the above anomaly is significant. A clear quiescence anomaly quantified by Q-parameters in space was "detected" in the epicentral region of the 2000 swarm. The test for earthquake swarms in the Izu Island region indicated that the increased *RTL* parameter could be a new potentially useful index for the risk alarm of earthquake swarms.

Acknowledgements

The author thanks the Japan Meteorological Agency (JMA) for providing the earthquake data and Dr A.O. Öncel and another anonymous reviewer for their insightful comments on the original manuscript. This study is supported by National Natural Science Foundation of China (No. 40474024) and the Scientific Research Foundation for the Returned Overseas Chinese Scholars, State Education Ministry, China.

References

Bendat, J.S., Piersol, A.G., 2000. Random Data: Analysis and Measurement Procedures. Wiley, New York.

Di Giovambattista, R., Tyupkin, Y.S., 2001. Cyclic migration of weak earthquakes between Lunigiana earthquake of October 10, 1995 and Reggio Emilia earthquake of October 15, 1996 (Northern Italy). Journal of Seismology 5, 147–156.

Huang, Q., 2004. Seismicity pattern changes prior to large earthquakes—an approach of the *RTL* algorithm. Terrestrial, Atmospheric and Oceanic Sciences 15, 469–491.

Huang, Q., Nagao, T., 2002. Seismic quiescence before the 2000 $M=7.3$ Tottori earthquake. Geophysical Research Letters 29, 1578, doi: 10.1029/2001GL013835.

Huang, Q., Sobolev, G.A., 2002. Precursory seismicity changes associated with the nemuro peninsula earthquake, January 28, 2000. Journal of Asian Earth Sciences 21, 135–146.

Huang, Q., Sobolev, G.A., Nagao, T., 1995. Characteristics of the seismic quiescence and activation patterns before the $M=7.2$ Kobe earthquake, January 17, 1995. Tectonophysics 337, 99–116.

Huang, Q., Öncel, A.O., Sobolev, G.A., 2002. Precursory seismicity changes associated with the $M_w=7.4$ 1999 August 17 Izmit (Turkey) earthquake. Geophysical Journal International 151, 235–242.

Japan Meteorological Agency, 2000. Recent seismic activity in the Miyakejima and Niijima-Kozushima region, Japan. Earth Planets Space 52, i–viii.

Kasahara, K., 1981. Earthquake Mechanics. Cambridge University Press, Cambridge.

Kossobokov, V.G., Keilis-Borok, V.I., 1990. Localization of intermediate-term earthquake prediction. Journal of Geophysical Research 95, 763–772.

Main, I., 1999. Applicability of time-to-failure analysis to accelerated strain before earthquakes and volcanic eruptions. Geophysical Journal International 139, F1–F6.

Molchan, G.M., Dmitrieva, O.E., 1992. Aftershocks identification: methods and new approaches. Geophysical Journal International 190, 501–516.

Nagao, T., Enomoto, Y., Fujinawa, Y., Hata, M., Hayakawa, M., Huang, Q., Izutsu, J., Kushida, Y., Maeda, K., Oike, K., Uyeda, S., Yoshino, T., 2002. Electromagnetic anomalies associated with 1995 Kobe earthquake. Journal of Geodynamics 33, 401–411.

Omori, F., 1900. Investigation of aftershocks. Report Imperial Earthquake Investigation Committee 30, 4–29.

Öncel, A.O., Wilson, T., 2002. Space-time correlations of seismotectonic parameters and examples from Japan and Turkey preceding the Izmit earthquake. Bulletin of the Seismological Society of America 92, 339–350.

Öncel, A.O., Wyss, M., 2000. The major asperities of the 1999 $M_w=7.4$ Izmit earthquake defined by the microseismicity of the two decades before it. Geophysical Journal International 143, 501–506.

Öncel, A.O., Main, I., Alptekin, Ö., Cowie, P., 1996. Spatial variations of the fractal properties of seismicity in the Anatolian Fault Zones. Tectonophysics 257, 189–202.

Öncel, A.O., Wilson, T., Nishizawa, O., 2001. Size scaling relationships in the active fault networks of Japan and their correlation with Gutenberg-Richter b values. Journal of Geophysical Research 106, 21827–21841.

Smirnov, V.B., 1998. Earthquake catalogs: evaluation of data completeness. Volcanology and Seismology 19, 433–446.

Sobolev, G.A., Tyupkin, Y.S., 1997. Low-seismicity precursors of large earthquakes in Kamchatka. Volcanology and Seismology 18, 433–446.

Sobolev, G.A., Tyupkin, Y.S., 1999. Precursory phases, seismicity precursors, and earthquake prediction in kamchatka. Volcanology and Seismology 20, 615–627.

Sobolev, G.A., Huang, Q., Nagao, T., 2002. Phases of earthquake's preparation and by chance test of seismic quiescence anomaly. Journal of Geodynamics 33, 413–424.

Uyeda, S., Hayakawa, M., Nagao, T., Molchanov, O., Hattori, K., Orihara, Y., Gotoh, K., Akinaga, Y., Tanaka, H., 2002. Electric and magnetic phenomena observed before the volcano-seismic activity in 2000 in the Izu Island Region. Proceedings of the National Academy of Sciences USA 99, 7352–7355.

Wyss, M., Martirosyan, A., 1988. Seismic quiescence before the M7,1988, spitak earthquake, Armenia. Geophysical Journal International 134, 329–340.

Wyss, M., Matsumura, S., 2002. Most likely locations of large earthquakes in the Kanto and Tokai areas, Japan, based on the local recurrence times. Physics of the Earth and Planetary Interior 131, 173–184.