The Correlation Between the Phase of the Moon and the Occurrences of Microearthquakes in the Tamba Region

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Abstract: *We study the correlation between the phase of the moon and the occurrence of microearthquakes in Tamba region which is close to the fault of the 1995 Kobe earthquake. Since the existence of the correlation after the Kobe earthquake has been suggested in the previous study, we investigate the statistical significance of the correlation in this study. Using point-process modeling and AIC (Akaike Information Criterion), we can confirm that the existence of the correlation is statistically significant and that the correlation is strong just after the Kobe earthquake and that then it becomes weaker year by year.*

1. Introduction

There are previous studies which made an attempt to find a correlation between occurrences of earthquakes and the phase of the moon, and *Katao* [2002] (referred to K2002 hereafter) is the one of these studies. K2002 reports that, after the 1995 Kobe earthquake, the occurrences of microearthquakes (MEs) correlated with the phase of the moon in Tamba region which is close to the focal region of the Kobe earthquake. K2002 examines the frequency distribution of the MEs after approximately two years after the occurrence of the Kobe earthquake, and showed that the frequency of the MEs varies depending on the phase of the moon.

In K2002, the statistical significance of the variation was not investigated. Thus, to confirm the significance, we apply a statistical analysis called "point-process modeling" [e.g., *Ogata,* 1983a] to the data examined in K2002. In the analysis, we investigate not only the significance of the correlation but also the temporal variation of the correlation.

2. Data

The earthquakes used in this study occurred at Tamba region, listed in the catalogue compiled by Disaster Prevention Research Institute (DPRI), Kyoto University, Japan. Tamba region is neighbor to the focal region of the 1995 Kobe earthquake, and the seismicity in this region increased after the occurrence of the Kobe earthquake [e.g., *Toda et al.,* 1998]. We make a dataset of earthquakes inside a rectangular area which is the same as defined in K2002. Considering the detection capability, the earthquakes of $M \geq 1.4$ are used.

3. Statistical Analysis Using Point-Process Modeling

To examine the statistical significance of the correlation shown in K2002, we did a statistical analysis called "point-process modeling" [e.g., *Ogata*, 1983a]. To investigate the periodicity of seismicity with point-process modeling, *Ogata* [1983a] suggested the following type of function as $\lambda(t)$:

$$\lambda(t) = \mu + (\text{trend}) + (\text{cluster}) + (\text{periodicity}), \tag{1}$$

where $\lambda(t)$ is the intensity function which shows the occurrence rate of earthquakes in unit time (one day, in this study). We use a polynomial function to indicate trend, ETAS model [*Ogata,* 1988] to indicate cluster, and trigonometric functions to indicate periodicity. Thus, the intensity function used in this study is as follows:

$$\begin{aligned}\lambda(t) &= \mu + \sum_{k=1}^{n} a_k t^k + \sum_{i;t_i<t} \frac{K\exp(\alpha(M_i - M_z))}{(t - t_i + c)^p} + \sum_{k=0}^{L_1} A_{1k} t^k \cdot \sin\theta(t) + \sum_{k=0}^{L_1} B_{1k} t^k \cdot \cos\theta(t) \\ &\quad + \sum_{k=0}^{L_2} A_{2k} t^k \cdot \sin(2\theta(t)) + \sum_{k=0}^{L_2} B_{2k} t^k \cdot \cos(2\theta(t)). \qquad (2) \\ &\quad (a_k,\ K,\ c,\ p,\ \alpha,\ A_{1k},\ B_{1k},\ A_{2k},\ B_{2k}\text{: parameters})\end{aligned}$$

where t_i and M_i are an occurrence time and magnitude of i-th ME, respectively. M_z indicates the lower threshold of the magnitude in our dataset, and $\theta(t)$ is a function which converts actual time t into the phase angle. As the phase angle, we assigned $0°$ or $360°$ to the times of new moon, and $180°$ to the times of full moon. Then, the phase angle is assigned to the time linearly from $0°$ to $180°$ or from $180°$ to $360°$. Note that $\theta(t)$ and $2\theta(t)$ indicate the phase angle related with a synodic and a half-synodic month, respectively.

In equation (2), we consider four kinds of constraint for the orders L_1 and L_2: (i) $L_1 = L_2 = 0$; (ii) $L_2 = 0$; (iii) $L_1 = 0$; and (iv) no constraint. Each constraint corresponds to the case when we consider (i) no triggering effect related with the phase of the moon, (ii) only the effect related with a synodic month, (iii) only the effect related with a half-synodic month, and (iv) the effect related with both a synodic and a half-synodic month.

For each of the four cases, we estimate the parameters which provide the best fit to the observed time series of the MEs using maximum likelihood method [e.g., *Ogata,* 1983b]. We also estimate the AIC (Akaike Information Criterion) [*Akaike,* 1974] for each of them. Among the cases, the case whose AIC is the smallest is considered to offer the best fit to the observed occurrences of the MEs. Note that the orders N's, L_1's and L_2's are also determined using AIC.

We analyze the MEs during approximately four years after the 1995 Kobe earthquake; from 3:00 on 17 January 1995 to 3:00 on 17 December 1999 (JST). The numbers of used MEs are 5438. The AICs and the orders N's, L_1's and L_2's of the four cases are shown in Table 1. The AIC of the case (iv) is the smallest among the four cases.

Since the cases (i), (ii), and (iii) are restricted versions of the case (iv), the difference of the AIC of the case (iv) and those of the other cases can be converted into the log-likelihood ratio statistic [e.g., *Ogata,* 1983b]. Using this feature, we can estimate the probability that the fit of the case (iii) whose AIC is the second smallest is better than the case (iv). Following the values shown in Table 1, the estimated probability is 2.56%, which is too small to accept the null hypothesis. This implies that the correlation between the activity of the MEs and the phase of the moon is statistically significant, and we should consider the triggering effect related with both a synodic and a half-synodic month. Figure 1(a) shows the intensity of the trigonometric part, which represents the periodicity. The value of the intensity after the moments of new/full moon is generally higher compared with that in the other period.

Since

$$g_i(t) = \sqrt{(\sum_{k=0}^{L_i} A_{ik} t^k)^2 + (\sum_{k=0}^{L_i} B_{ik} t^k)} \quad (i = 1, 2) \qquad (3)$$

shows the amplitudes of the intensity functions related with a synodic or a half-synodic month, we plot these in Figure 1(b). These are in maximum just after the occurrence of the 1995 Kobe earthquake, and generally decreases as time elapsed.

We also apply the same statistical test to the dataset during four years before the occurrence of the Kobe earthquake; from 0:00 on 17 January 1993 to 0:00 on 17 January 1995 (JST). The case (i) is chosen as the best one; the significant correlation is not found.

4. Discussion

After the Kobe earthquake, the seismicity rate in Tamba region was increased compared with before, and this increase is assumed to be caused by increase of static stress due to the main rupture of the Kobe earthquake [e.g., *Toda et al.,* 1998]. As mentioned in the previous sections, the significant correlation is found only after the Kobe earthquake and not found before. Additionally the correlation is the most remarkable just after the Kobe earthquake, and becomes weaker. This feature supports our interpretation that rupture of the Kobe earthquake makes stress/strain state in Tamba region critical and that the seismicity correlates with the phase of the moon.

Recent laboratory experiments imply the occurrence of acoustic emissions/earthquakes affected by the amplitudes of stress/strain changes [*Lockner and Beeler*, 1999]. *Yamamura et al.* [2003] examine the seismic velocity observed in a vault at the coast of Miura Bay, Japan and find the temporal variation of the velocity with 14-days (approximately a half-synodic month) periodicity. These studies suggest that the changes of the amplitudes of stress/strain caused by the phase of the moon could affect the seismicity or the physical properties of the earth, and support our results in this study.

One may note that the feature that not only $2\theta(t)$ but also $\theta(t)$ is correlated with the occurrence of the MEs. A suggestion for the cause of this feature is that the maximum amplitude of stress/strain changes varies for new and full moon. Using the program of *Agnew* [1997], we calculated the strain changes at the center of the focused area. In some periods, it is remarkable that the maximum amplitude of strain changes varies between around times of new and full moon. Our results may suggest that this variation would influence the occurrence of the earthquakes and that we should include the variation directly for more precise modeling of the occurrence of earthquakes.

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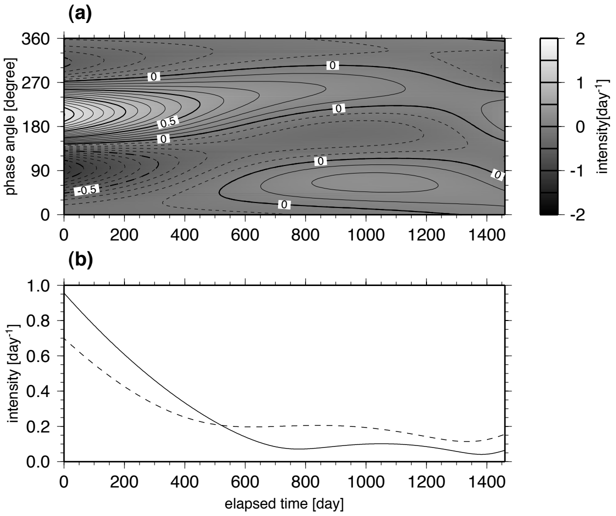

Figure 1 *(a) Temporal variation of the intensity functions of the trigonometric part in equation (2) obtained by the analyses of the MEs from 12:00 on 17 January 1995 to 12:00 on 17 January 1999. The vertical axis indicates the elapsed days since 12:00 on 17 January 1995. (b) Temporal variations of* $g_i(t)$ *as shown in equation (3), which denotes the amplitudes of the intensity functions of the trigonometric part in equation (2). The solid and dotted lines correspond to the amplitudes related with a synodic (i=1 in equation (3) and a half-synodic month (i=2), respectively.*

constraint	(i)	(ii)	(iii)	(iv)
(N, L_1, L_2)	(3, 0, 0)	(3, 3, 0)	(3, 0, 3)	(3, 3, 3)
AIC	−4933.03	−4938.84	−4936.18	−4942.14*

* The minimum value of AIC is obtained.

Table 1 *The AICs and the orders* N*,* L_1 *and* N_2 *of the polynomial function representing trend, temporal variations of periodicities related with a synodic and a half-synodic month using the intensity function as shown in equation (2), for the analyses of the MEs from 12:00 on 17 January 1995 to 12:00 on 17 January 1999.*