FAST TRACK PAPER

An improved region–time–length algorithm applied to the 1999 Chi-Chi, Taiwan earthquake

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SUMMARY

By means of the region–time–length (RTL) algorithm, which is widely used for investigating the precursory seismicity changes in China, Italy, Japan, Russia and Turkey, we examine the precursory seismic activity occurred prior to the 1999, $M_w = 7.6$, Chi-Chi earthquake around its epicentre. Based on our calculation of the *RTL* values, the epicentral area has been found to strongly exhibit the signature of anomalous activity, associated with the seismic quiescence and activation, before the main shock. Also proposed in this study is a helpful method for determining two important parameters used in the RTL analysis, the characteristic time and distance. Such method will largely reduce the ambiguity in the original RTL algorithm.

Key words: Chi-Chi earthquake, region–time–length algorithm, seismic activation, seismic quiescence.

1 INTRODUCTION

Two phases in seismicity change before a forthcoming, major earthquake are widely observed, which are the seismic quiescence and activation (Wyss & Habermann 1988; Jaume & Sykes 1999). While the literature abounds in individual case studies of seismic quiescence or seismic activation, some systematic tests for such precursory phenomena also exist (Bowman *et al.* 1998; Gross & Rundle 1998; Zoller *et al.* 2002). Most researches on seismic activation emphasize the increasing activity of moderate-sized earthquakes (Sykes & Jaume 1990). On the other hand, vagueness hovered regarding earthquake magnitude for which the quiescence is observed (Wiemer & Wyss 1994; Huang *et al.* 2001; Zoller *et al.* 2002). Probably, the seismic quiescence could be marked by the low activity for all magnitude bands of earthquakes and the activation only for moderate earthquakes.

The Chi-Chi earthquake (Fig. 1) with moment magnitude 7.6 struck central Taiwan on 1999 September 21 (or at UTC 17:47 September 20), which was the largest earthquake that occurred on the Taiwan Island in the 20th century. Chen (2003) investigated the accelerating activity of moderate-sized earthquakes before the Chi-Chi earthquake and pointed out that seismic activation of earthquakes with magnitude larger than 5 started at the end of 1993, lasting about 6 yr up to the main shock. Carefully examining the frequency–magnitude distributions of three stages before the Chi-Chi earthquake (Figure 3 in Chen 2003), the change in seismicity is actually complicated. While only seismic activation of moderate-sized earthquakes ($M \geq 5$) occurred in the second stage (Figure 3b in Chen 2003), the third stage (Figure 3c in Chen 2003) seems a hybrid of seismic quiescence for small-sized events ($M < 5$) and activation for moderate events. In the context of self-organizing spinodal model of earthquake fault systems (Rundle *et al.* 2000), the time evolution of the frequency–magnitude distributions of earthquakes in Taiwan before the Chi-Chi earthquake represents a typical example of seismic activation for moderate earthquakes, demonstrating a systematically temporal change in seismicity.

Following the previous investigation of the temporal change in seismicity in the whole Taiwan region (Chen 2003), we further investigate the seismicity variation for the epicentre area of the Chi-Chi event before the catastrophic main shock. We explore this issue by the region–time–length (RTL) algorithm, which has been widely used in Italy, Russia, Japan, Turkey and China (Sobolev & Typukin 1997; Kopylova *et al.* 1998; Sobolev & Typukin 1999; Di Giovambattista & Tyupkin 2000; Huang *et al.* 2001, 2002; Huang & Nagao 2002; Huang 2004; Jiang *et al.* 2004). We will also propose an important method determining two free parameters used in the original RTL algorithm, thus reducing the intrinsic ambiguity for the RTL analysis.

2 RTL ALGORITHM

The RTL algorithm has been successfully used to detect precursory seismic activation and quiescence of the 1995 $M = 7.2$ Kobe (Japan), 1997 $M = 7.8$ Kronotskoye (Kamchatka, Russia), 1999 $M = 7.4$ Izmit (Turkey), 2000 $M = 7.3$ Tottori (Japan) earthquakes (Kopylova *et al.* 1998; Huang *et al.* 2001, 2002; Huang & Nagao 2002). We, therefore, consider the RTL algorithm a helpful technique to reveal the significantly precursory activity occurred before large earthquakes. This approach has been clearly described in, for

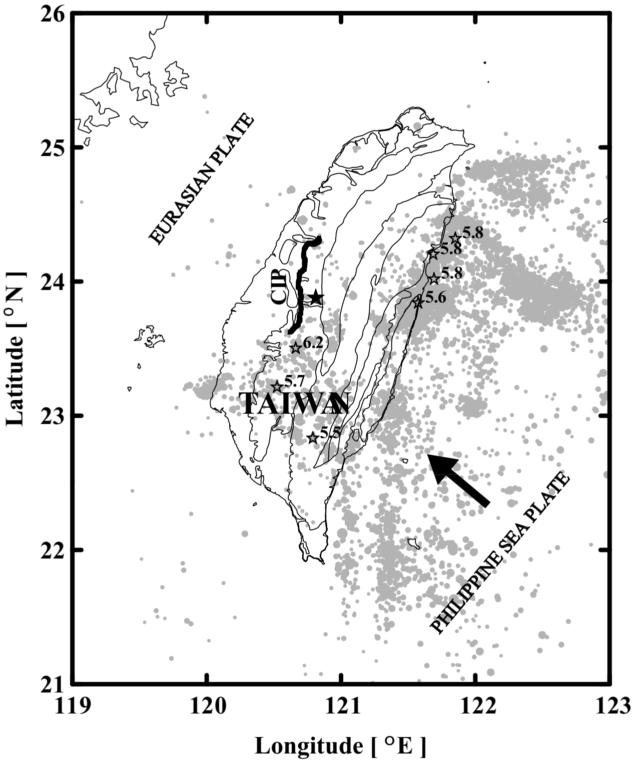

Figure 1. Map showing the epicentres of earthquakes used in this study (dots) and the Chi-Chi main shock (star). CLP = the Chelungpu fault. Thick arrow indicates the direction of relative motion between the Eurasian Plate and the Philippine Sea Plate. Open stars are earthquakes larger than 5.5, occurred within a characteristic distance of $2r_0$ from the epicentre of the Chi-Chi main shock.

example, Huang *et al.* (2001, 2002) and Huang (2004). Here we give a concise review.

The basic idea of the RTL algorithm is to assign a weighting *RTL* value at a given spatiotemporal point (x, y, t), which is contributed from events occurred in a prescribed space–time window with the characteristic distance and time. A related subset to the investigated point (x, y, t) with n earthquakes could be selected from the original catalogue. See the next section for the selection criterion. For the ith event, let l_i be the rupture size, t_i the occurrence time and r_i the spatial distance from the investigated point (x, y) to the epicentre. The rupture size l_i can be empirically estimated from magnitude M_i by the relation $\log l_i$ (in km) $= 0.5\,M_i - 1.8$ (Kasahara 1981). For instance, the rupture length of the $M = 7.6$ Chi-Chi earthquake derived from this relation is 100 km, which is quite close to the field observation (Fig. 1). Then three dimensionless functions, R, T and L, describing the influence weights of location, occurrence time and magnitude of those n earthquakes are defined as

$$R(x, y, t) = \sum_{i=1}^{n} \exp\left(-\frac{r_i}{r_0}\right)$$

$$T(x, y, t) = \sum_{i=1}^{n} \exp\left(-\frac{t - t_i}{t_0}\right)$$

$$L(x, y, t) = \sum_{i=1}^{n} \left(\frac{l_i}{r_i}\right), \quad (1)$$

where r_0 and t_0 are the characteristic distance and time associated with the spatiotemporal criteria. R, T and L functions are further detrended with their own background linear functions and normalized by their own standard deviations σ_R, σ_T, and σ_L, respectively. Accordingly, a prognostic *RTL* function can be calculated at every spatiotemporal point (x, y, t), which is simply the product of the three detrended and normalized R, T and L functions.

Functionally, the *RTL* weight contributed from an event is greater when that event is closer to the investigated spatiotemporal point (x, y, t), that is, closer to the grid point (x, y) in space and closer to t in time, and larger in magnitude. A change in *RTL* value means a change in seismicity rate (activation or quiescence) with respect to the background level around the investigated point (x, y, t).

3 RTL ANALYSIS AND RESULTS

For our study, we used an earthquake catalogue maintained by the Central Weather Bureau (CWB) of Taiwan. This catalogue includes the data of earthquakes occurred in and around Taiwan since 1973. The data consists of occurrence time, magnitude and location given by east longitude, north latitude and focal depth. For removing aftershocks, we used a declustering procedure proposed by Reasenberg (1985). The selected events for the RTL analysis are those with magnitude equal to or larger than a lower cut-off magnitude 3 during the span through 1991 January 1 to 1999 September 20 (before the Chi-Chi event), which fulfils the requirement of completeness of the earthquake data (Wang & Shieh 2004; Lee & Tsai 2005). Other criteria for selecting the earthquake data are: the focal depth $d_i \leq$ 30 km; the epicentral distance $r_i \leq 2r_0 = 115$ km for a given grid point (x, y); and the occurrence time t_i fulfils that $(t - t_i) \leq 2t_0 =$ 1.9 yr for a given time step t. A depth of 30 km is about the thickness of seismogenic zone in the crust for the Taiwan region (Wang *et al.* 1994).

The test on the characteristic distance and time, r_0 and t_0, for the RTL analysis is shown in Fig. 2. Motivated by Huang *et al.* (2001) and Huang (2004), we here propose a systematical generalization of their correlation analysis for the RTL calculation. We calculated many sets of the *RTL* functions with various combinations of r_0 ranging between 25 and 100 km and t_0 between 0.25 and 2.5 yr, then computed the correlation coefficients over pairs of the *RTL* functions. It is expected that high correlation between two *RTL* functions could be found when their values of r_0 and t_0 approach the optimal values mostly stabilizing the pattern of the *RTL* function. There are 31 r_0s and 46 t_0s investigated in our analysis (Fig. 2). For any given t_0, there are 961 correlation coefficients calculated over pairs of the *RTL* functions with different r_0s. As shown in Fig. 2(a), at $t_0 = 0.95$ yr, the *RTL* functions with various r_0s would be highly similar to each other and ~80 per cent of the correlation coefficients calculated over pairs of the *RTL* functions are larger than 0.8, thus indicating an optimal t_0 of 0.95 yr. Similarly, for a given r_0, there are 2116 correlation coefficients obtained over pairs of t_0s. Shown in Fig. 2(b), ~50 per cent of the correlation coefficients are larger than 0.5 at $r_0 = 57.5$ km, thus indicating an optimal r_0 of 57.5 km. High correlation between the *RTL* functions could be also found for small t_0s (<0.5 yr) and r_0s (<40 km) in Fig. 2. However, due to limited data in such small spatiotemporal windows, high correlation seems statistically biased and should be ignored. It is interesting that, while such test on r_0 and t_0 was never shown in previous RTL studies (Di Giovambattista & Tyupkin 2000; Huang *et al.* 2001, 2002; Huang & Nagao 2002; Huang 2004; Jiang *et al.* 2004), the choices of r_0 and t_0 seems arbitrary in those studies, yet our values of r_0 and t_0 obtained from such test is quite close to those values used in previous studies. In addition, our test indicates the RTL analysis is much

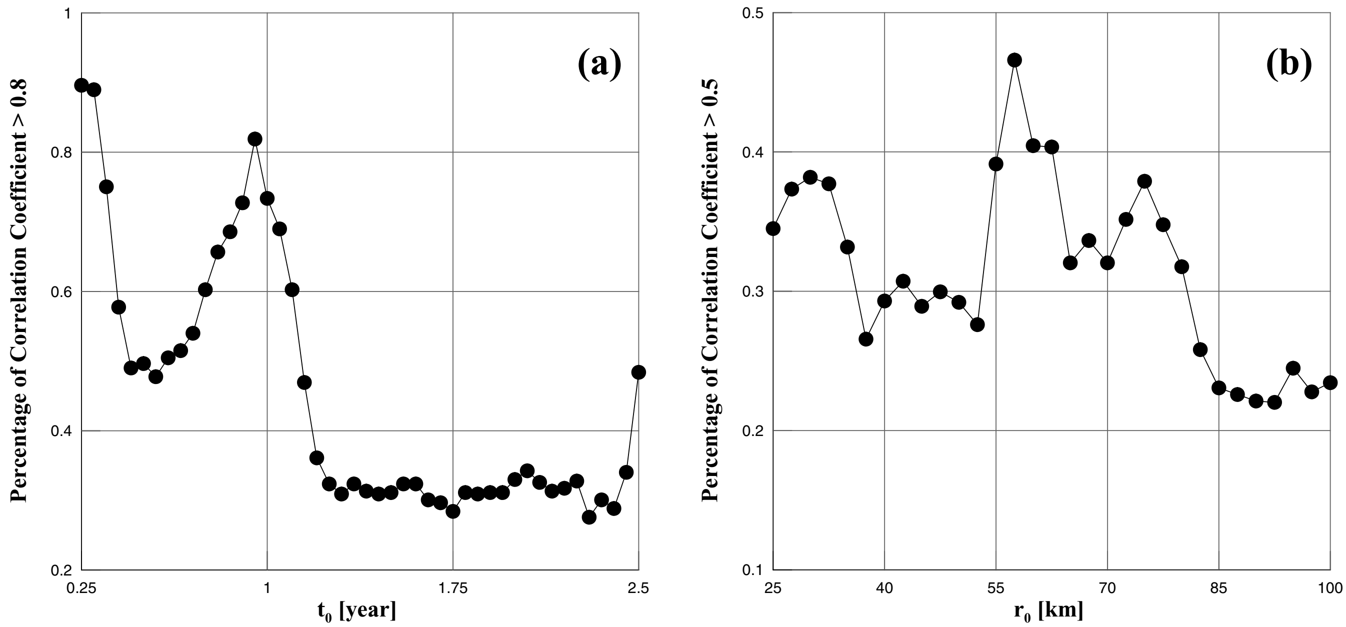

Figure 2. Test on the characteristic time and distance, t_0 and r_0, for the RTL analysis. For the detail explanation please see the text.

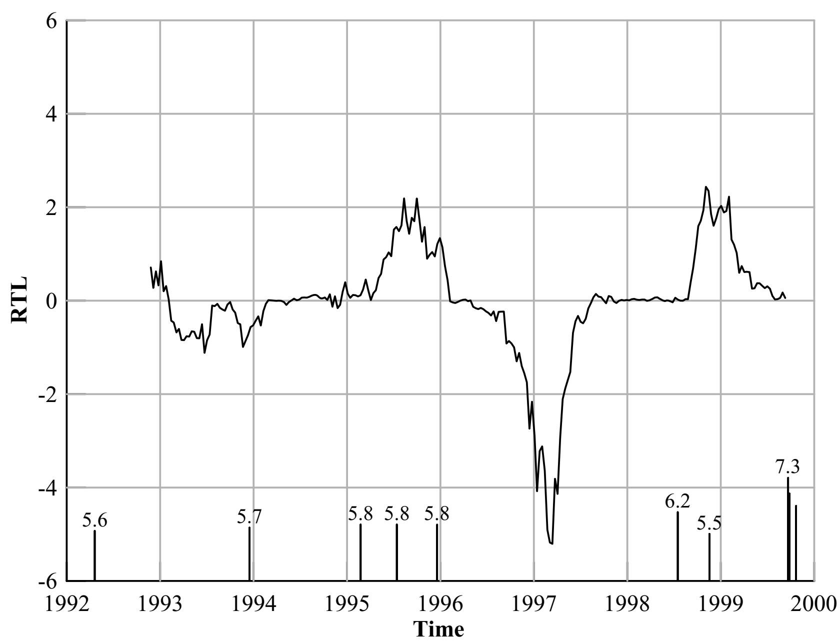

Figure 3. Temporal variation in the *RTL* function at the epicentre of the 1999 Chi-Chi earthquake. The bar chart indicates the occurrence time of earthquakes larger than 5.5, occurred within a characteristic distance of $2r_0$ from the epicentre of the Chi-Chi main shock; each number associated with each bar is the magnitude. Seismic activation appeared around 1999 and seismic quiescence can be found around 1997.

more affected by the choice of t_0 than r_0, which is consistent with the results obtained in Huang (2004, Table 2).

For the RTL analysis of the Chi-Chi earthquake, we calculated the temporal variation in the *RTL* function at its epicentre. Fig. 3 shows the *RTL* values from late 1992 to 1999 September, before the Chi-Chi main shock. An obvious seismic activation stage can be found in Fig. 3 around 1999, indicating that the phenomenon of seismic activation probably began from 1997, since for each time step t we actually counted the seismiciy in an interval of ∼2 yr before t. Note that a recovery stage from a local minimum of the *RTL* function to the background level was considered as the activation stage of seismicity in, for example, Huang & Nagao (2002). However, we prefer a definition of positive *RTL* values for the activation stage of seismicity, motivated by the self-organizing spinodal model (Rundle *et al.* 2000). Seismic quiescence, on the other hand, can be found around 1997, implying the seismic quiescence appeared during a time interval from 1995 to 1997. For testing the statistical significance of the observed quiescence anomaly we have adopted the stochastic test suggested in Huang *et al.* (2002) and Huang (2004). We generated 1000 realizations of random earthquake catalogue, calculated their *RTL* functions and estimated the occurrence probability of the negative RTL anomaly. The occurrence probability of an RTL negative anomaly with a minimum smaller than -5 and the duration longer than 1 yr, as we observed in the real catalogue (Fig. 3), is only about 2 per cent. Furthermore, the probability under one additional restricted condition, that requires the occurrence time of the negative anomaly is around 1997 (2.5 yr before the Chi-Chi earthquake), reduces to about 0.5 per cent. The probability estimation concludes that the seismic quiescence observed before the Chi-Chi earthquake is not an outcome of a random process.

The change in the *RTL* function, therefore, suggests the epicentral area before the catastrophic Chi-Chi main shock first experienced the seismic quiescence, which was then followed by the seismic activation. For comparison, the occurrence time of earthquakes larger than 5.5, occurred within a distance of $2r_0$ from the epicentre of the Chi-Chi main shock (Fig. 1), is also shown in Fig. 3.

In Fig. 3, a large positive anomaly of the *RTL* function can be also found during a time interval of (1995, 1996), which is most probably related to the cluster of three large earthquakes occurred in the eastern Taiwan (Fig. 1). It is not so clear for the moment if the positive anomaly is associated with the preparation of the Chi-Chi earthquake. We notice that a similar result was also obtained in the RTL analysis for the 1999 Izmit earthquake by Huang *et al.* (2002).

4 CONCLUDING REMARK

The phenomenon of precursory seismic activation and quiescence before the Chi-Chi earthquake has been explored in this study. Using the RTL algorithm, the epicentre of the Chi-Chi earthquake has been found to strongly exhibit the signature of anomalous activity, including a period of seismic quiescence followed by seismic activation. We, therefore, conclude that the 1999 Chi-Chi, Taiwan, earthquake could be a typical example of seismic activation and quiescence.

By means of the RTL analysis, it seems now possible to shed light on the relevant preparation process of a forthcoming, catastrophic earthquake (Di Giovambattista & Tyupkin 2000; Huang *et al.* 2001, 2002; Huang & Nagao 2002; Huang 2004; Jiang *et al.* 2004). Without question, retrospective analysis is important to understand the preparation process of large earthquakes. However, it is also definitely critical to evaluate the validity of retrospective analysis. This is particularly true when some free parameters are involved into the retrospective analysis, such the so-called characteristic distance r_0 and time t_0 in the RTL algorithm. We have demonstrated in this paper an auxiliary tool for determining those two free parameters in the original RTL analysis. Such an auxiliary tool can thus reduce the ambiguity for choosing those free parameters in the RTL analysis.

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