

Seismic Quiescence before the 1999 Chi-Chi, Taiwan, M_w 7.6 Earthquake

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Abstract The Chi-Chi, Taiwan, earthquake of 20 September 1999 was preceded by a notable decrease of the regional seismicity rate. The anomalous period started in January 1999 and lasted about 9 months, up to the occurrence of the mainshock, as revealed from analyzing the Taiwan catalog data from 1 January 1994 to 20 September 1999. Our results indicate that the mean seismicity rate is 435 events per month with a standard deviation of 78 events for earthquakes with magnitude above 2.0. During the anomalous period, seismicity rates fell outside the range of one standard deviation with a mean value of 314 events per month. There was also a consistent trend of decreasing regional b -value as well as notable increases of seismic activity in areas surrounding the Chi-Chi earthquake source region via the Z-test map (ZMAP) analysis.

Introduction

Seismic precursors are an important but controversial topic. Among most of the reported precursors, seismic quiescence, which is defined as a significant decrease of the mean seismicity compared to the preceding background rate, is one that has received considerable attentions (Mogi, 1979; Wyss and Habermann, 1988; Wiemer and Wyss, 1994; Huang *et al.*, 2001; Huang and Nagao, 2002; Huang, 2004). We wish to examine whether there had been significant seismic quiescence as an observable precursor prior to the catastrophic Chi-Chi earthquake.

Taiwan is located on the western Circum-Pacific seismic belt. In the vicinity of Taiwan, the Philippine Sea plate subducts northward under the Eurasia plate along the Ryukyu trench to the northeast of Taiwan, whereas the Eurasia plate subducts eastward under the Philippine Sea plate off the southern tip of Taiwan. Tectonically, most of the Taiwan region is under northwest–southeast compression with a measured convergence rate of about 8 cm/year. Many disastrous earthquakes have occurred in the past, and those that have occurred from 1900 to 1999 are usually well documented (Fig. 1). These documented earthquakes may be grouped into two general categories: the earthquakes associated with the subduction of the Philippine Sea plate northward under the Eurasia plate (e.g., near and offshore of Hualien), and the ones associated with active faults in western Taiwan.

The 1999 M_w 7.6 Chi-Chi earthquake (Fig. 2) is the largest event on the Taiwan island in the last century (Shin *et al.*, 2000; Wu *et al.*, 2000). It caused 2456 casualties, 11,306 injuries, and about \$4 billion in property damage. There was not any early warning reported before the occurrence of the Chi-Chi earthquake. However, a detailed post-examination of the seismicity reveals an interesting anomaly that occurred about 9 months prior to the mainshock, that is,

the seismic activity had been significantly subdued for the Taiwan region. The regional b -value of the Gutenberg–Richter law of the same period is also consistently lower. We report, in this study, the monthly changes of seismicity, b -values, and Z-test map (ZMAP) analysis (Wiemer and Wyss, 1994) before the Chi-Chi earthquake to highlight the anomalies that might shed light on the study of precursors of large events.

Data

We analyze the catalog data from the Central Weather Bureau Seismic Network (CWBSN) in this study. The CWBSN consists of a central recording system with 73 telemetered stations (Fig. 2, solid squares) that are equipped with three-component S13 seismometers. Seismic signals digitized at 12 bits and 100 samples per second from each station are transmitted via dedicated telephone lines to the center station located in Taipei. Seismic signals are examined to manually pick the P and S arrivals for earthquake location and to determine the magnitude M_L (Shin, 1993).

The CWBSN system was operated in triggered-recording mode before the end of 1993. Since then, operation has changed to continuous-recording mode and manual identifications of earthquake events. This has greatly enhanced the sensitivity of earthquake detection. We screened the catalog data during the period from 1994 to the occurrence of the Chi-Chi earthquake, and picked those epicenters located on land or within 20 km of the coastlines of Taiwan and with a focal depth less than 40 km. As a result, there were 66,069 events selected in this study (Fig. 2). For these events, distributed within the region well and uniformly covered by the CWBSN, Chang (2004) has reported that the regional mag-

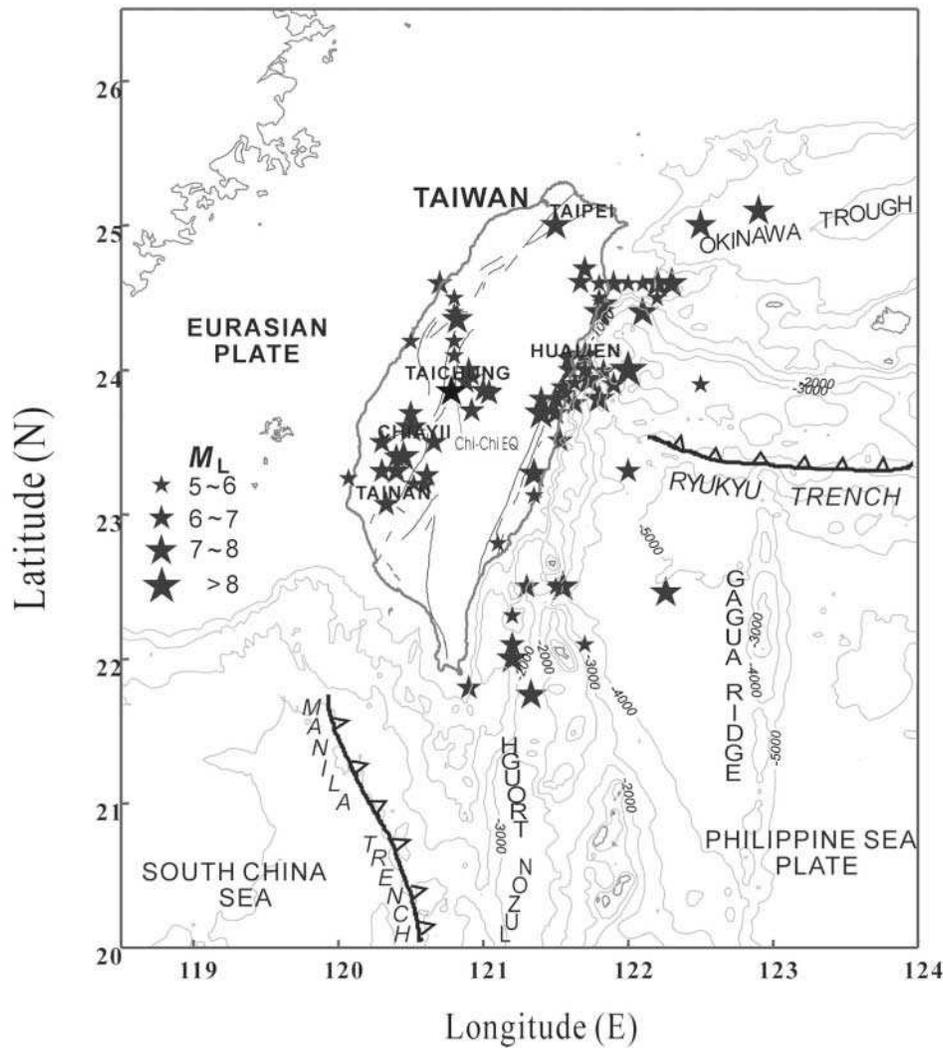


Figure 1. Epicenter distribution of disastrous earthquakes during 1900–1999 in the Taiwan area. These earthquakes may be divided into two general classes: the earthquakes associated with the subduction of the Philippine Sea plate northward under the Eurasia plate, and the ones associated with active faults in western Taiwan.

nitude completeness (M_C) is about 2.0. Furthermore, the study region is believed to be located well within the critical region of the Chi-Chi earthquake based on Bowman *et al.*'s (1998) discussion that the critical radius of the affected seismicity prior to an M 7.5 earthquake is more than 300 km.

We first derive the regional Gutenberg–Richter distribution and generate the frequency–magnitude plot (Fig. 3) of these selected events. Least-square regression results in the following distribution:

$$\log N = 6.74 - 1.05 M_L, \quad (1)$$

where N is the number of events with a magnitude equal or larger than M_L , and the b -value is thus 1.05 for this data set. The minimum magnitude of completeness, M_C , is about 2.0.

Temporal Variations of the Earthquake Number and the b -value

Aftershock activity generally masks temporal variations of the earthquake numbers and the related statistics. We chose to eliminate the aftershock sequences from our data set following other previous studies (e.g., Huang, 2004). We applied the time and spatial double-link cluster-analysis method to eliminate the aftershocks. This method is similar to the single-link cluster-analysis method proposed by Davis and Frohlich (1991). We removed aftershock sequences for those mainshocks with $M > 4.5$ using 3 days and 5 km as the linking parameters.

The aftershock-elimination procedure took away 8590 events, 14% of the total, from the data set. The monthly occurrence rates from 1994 to the occurrence of the Chi-Chi

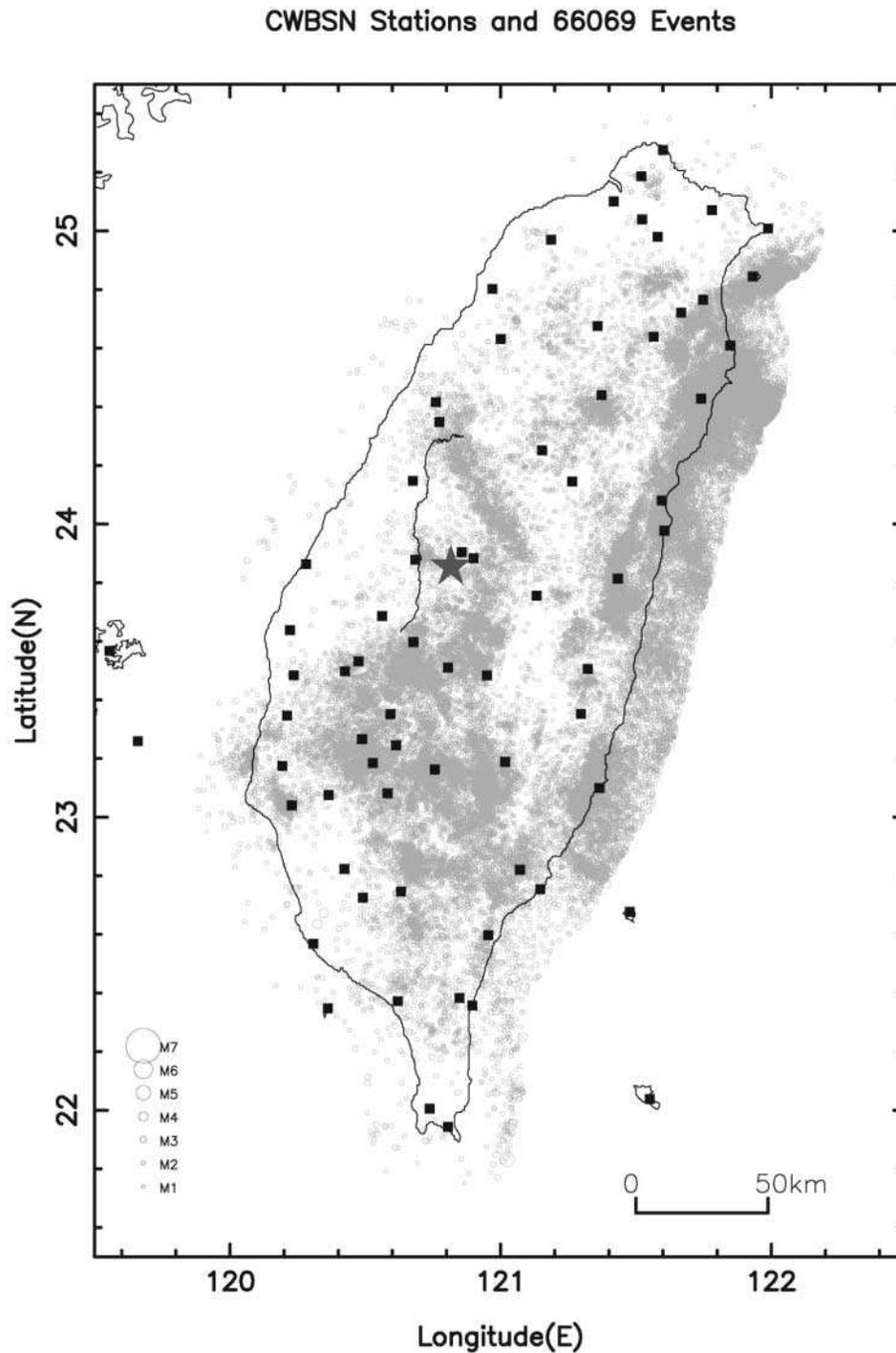


Figure 2. Epicenters of the selected 66,069 events used in this study (open circles). The locations of the seismic stations of the Central Weather Bureau Seismic Network (CWBSN) are marked by solid squares. The epicenter of the Chi-Chi earthquake is depicted by the star, and the solid line marks the surface rupture.

earthquake are calculated by counting events with $M_L > 2.0$ for every month and then normalizing the counts to the duration of 30 days. The average occurrence rate is 435 events per 30 days with a standard deviation of 78 events. It is clear that starting in January 1999, 9 months prior to the Chi-Chi

earthquake, a significant low-seismicity period emerged, with monthly event-occurrence rates falling outside the one-standard-deviation range (Fig. 4a).

The regional temporal variation of the b -value is also examined monthly (Fig. 4b) within the same period. The

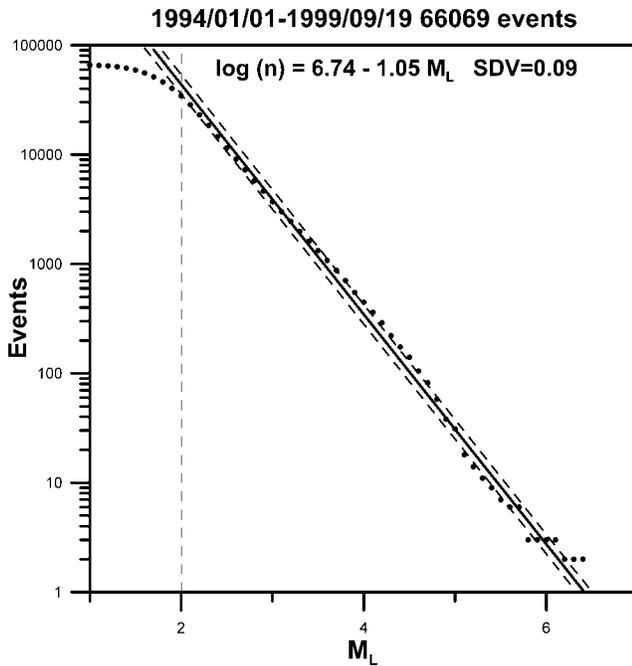


Figure 3. The log-log plot of the frequency-magnitude distribution of the selected events (dots). The solid line results from the least-squares regression, and the two dashed lines mark the range of one standard deviation. Magnitude completeness is 2.0 for the CWBSN.

average amounts to the value of 0.97 with a standard deviation of 0.10. Although there are no significant low or high anomalies, it exhibits a consistent decreasing trend during the low-seismicity period before the occurrence of the Chi-Chi earthquake.

To clarify the attribution of the observed seismicity reduction, we further examined the monthly occurrence rate for larger events with $M_L > 4.0$ only, and did not find significant reduction in the period from 1 January 1999 to 19 September 1999 (Fig. 4c). In other words, the observed seismicity reduction and the decreasing pattern of the b -value can be attributed essentially to the quiescence of smaller events with $M_L < 4.0$.

Results from the ZMAP Analysis

To establish the spatial distribution of the seismic quiescence mentioned earlier, we have applied the ZMAP method (Wiemer and Wyss, 1994) to the data extracted from different segments within the quiescence period. We first calculated the regional Z -values for the period from 1 January 1999 to 19 September 1999, a latter period of the seismic quiescence (from 1 January 1994 to 19 September 1999), for events with $M_L > 2.0$, focal depth less than 40 km, and the region bounded by 21.5° N to 25.5° N and 119.5° E to 122.5° E. The spatial grid spacing is set to 0.05° , yielding a resolution radius of about 20 km. The bin length is set to

60 days. For each spatial pixel, the local Z -value is then calculated by the equation

$$z(t) = (R_{\text{all}} - R_{\text{cal}}) / \sqrt{\frac{\sigma_{\text{all}}^2}{n_{\text{all}}} + \frac{\sigma_{\text{cal}}^2}{n_{\text{cal}}}}, \quad (2)$$

where R_{all} and R_{cal} are the mean seismicity rate within that pixel in the overall period and the considered time window, respectively; σ_{all} and σ_{cal} are the standard deviations of seismicity rate; and n_{all} and n_{cal} are the number of samples in these periods. A positive Z -value thus indicates a decrease in seismicity, whereas a negative Z -value implies a rise in seismicity.

The calculated Z -value ranges from -3.37 to 6.75 (Fig. 5a). Most of the Taiwan region is in the high positive Z -value (blue areas in Fig. 5a). This implies significant seismicity reduction, mainly for smaller events as discussed earlier, especially for the region of eastern Taiwan, where the Z -values easily exceed 3.0. Interestingly, it should be pointed out that there is simultaneously significant seismicity increasing, marked by the negative Z -values, in the areas surrounding the Chi-Chi earthquake rupture regions (star and solid line in Fig. 5a).

We also calculated the regional Z -values for the period from 1 January 1995 to 31 December 1996, a relatively earlier segment of the 1 January 1994–19 September 1999 quiescence period. The calculated Z -value ranges from -2.42 to 4.92 (Fig. 5b). Most of the eastern Taiwan region is now demarcated by the negative Z -values (red areas in Fig. 5b), and is in general closing to the background seismicity of the Taiwan region as compared to the anomalous period from 1 January 1999 to 19 September 1999.

Summary

Quiescence of seismicity (Ishida and Kanamori, 1977, 1978; Wyss and Martirosyan, 1998; Zhang *et al.*, 1999; Huang *et al.*, 2001; Huang and Nagao, 2002; Huang, 2004) as well as the decreasing b -value (e.g., Zhang *et al.*, 1999) before large earthquakes have been documented previously. We report, in this study, similar observations that last for about 9 months prior to the Chi-Chi earthquake. Most of the previously reported seismic-quiescence periods before the catastrophic events last from 1 to 2.5 years, and the duration of the subsequent seismic activation generally lasted for several months (Huang, 2004). We did not detect a significant seismic activation period for the Chi-Chi earthquake based on the temporal variation for the Taiwan region. However, there seems to be local seismic activation around the Chi-Chi earthquake rupture region. The raised seismic activity around the Chi-Chi earthquake rupture region as revealed from the ZMAP analysis, along with the general subdued activity in the background, especially to the eastern area where the tectonic compression loading originates, is an interesting feature that deserves further attention. Since the

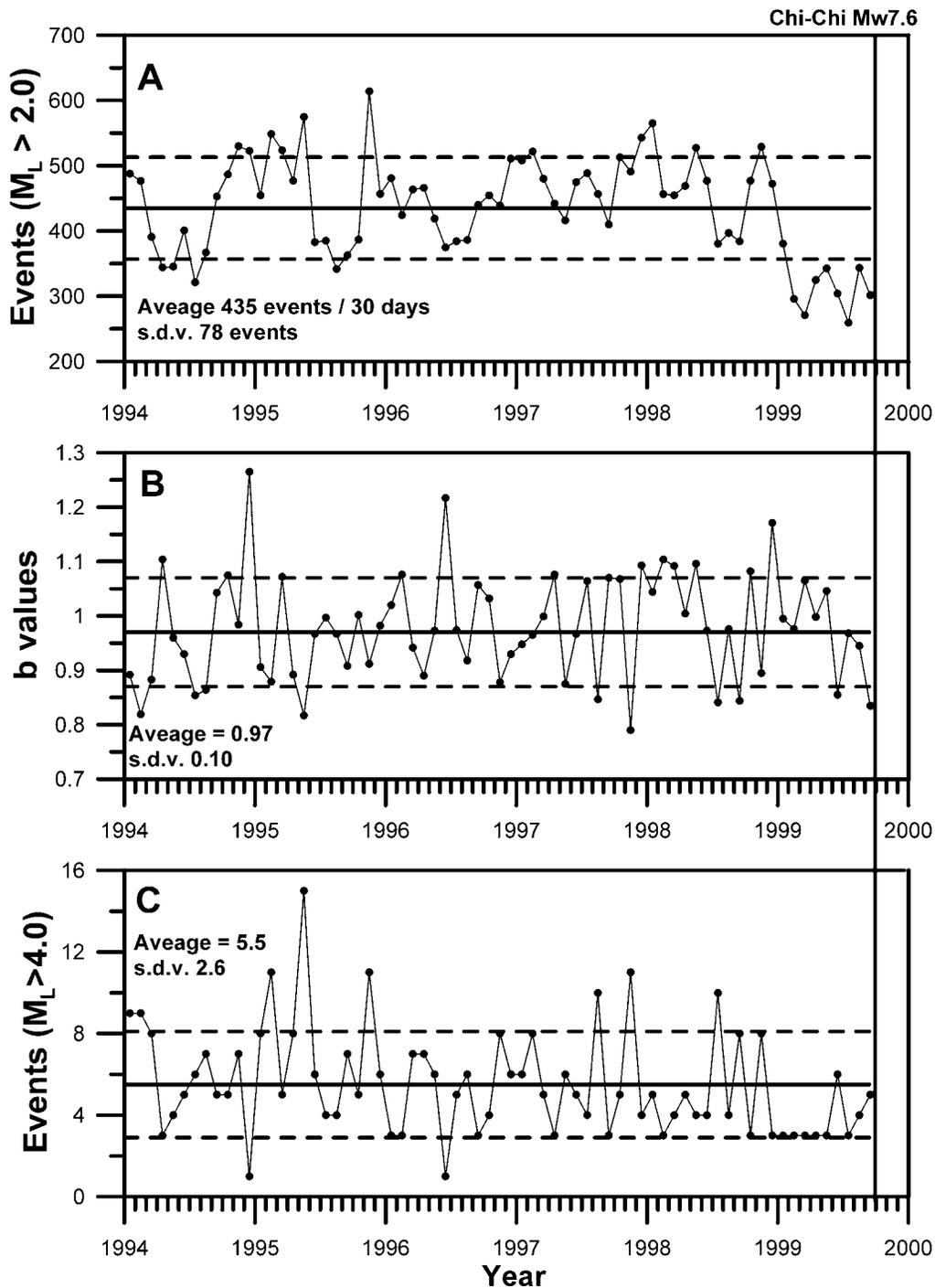


Figure 4. (A) Monthly event counts for $M_L > 2.0$; (B) monthly b -value variations; (C) monthly events counts for $M_L > 4.0$ from 1994 to the occurrence of the Chi-Chi earthquake. The solid line indicates the least-squares mean, and the two dashed lines show the range of one standard deviation.

seismic quiescence can be attributed mainly to the reduction of smaller events, one bold speculation is that the tectonic stress loading from the east has caused the closure of existing microfractures to the east, which then results in the migration and accumulation of strains to the west and eventually activates the Chi-Chi earthquake.

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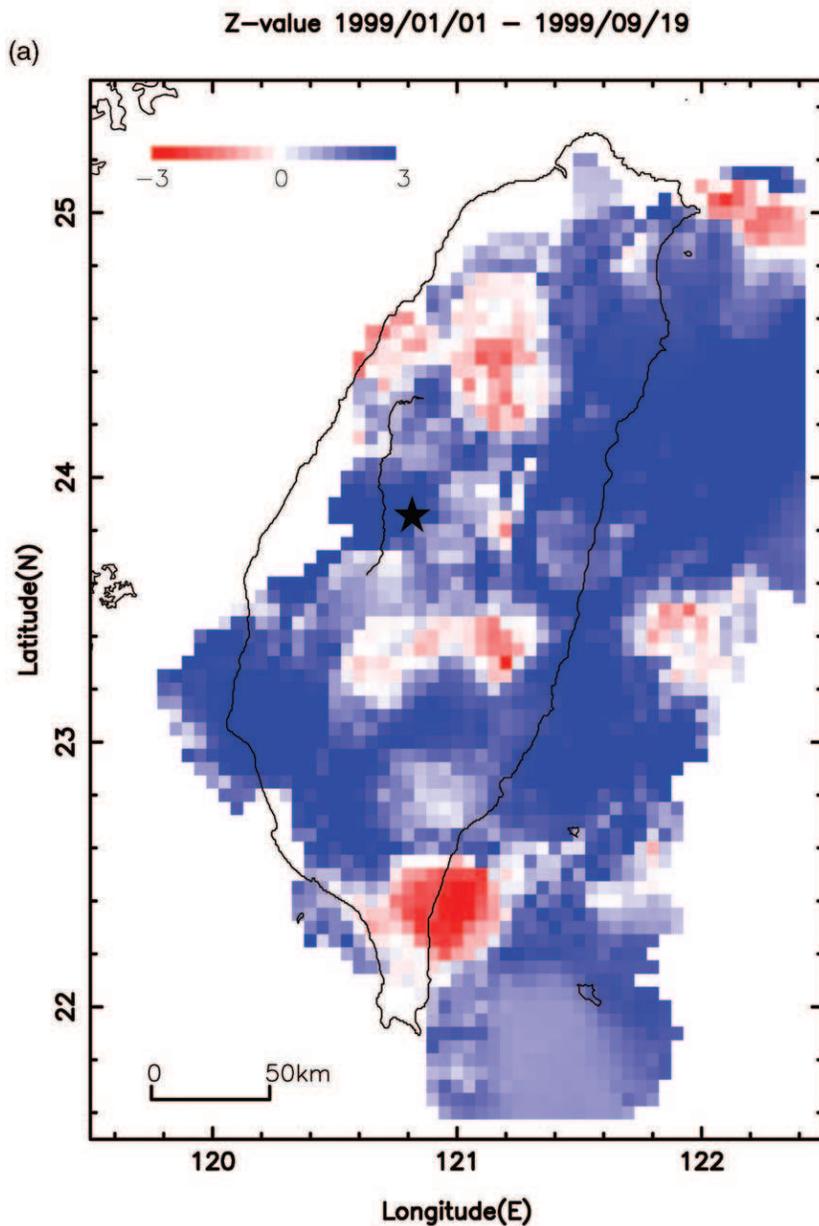
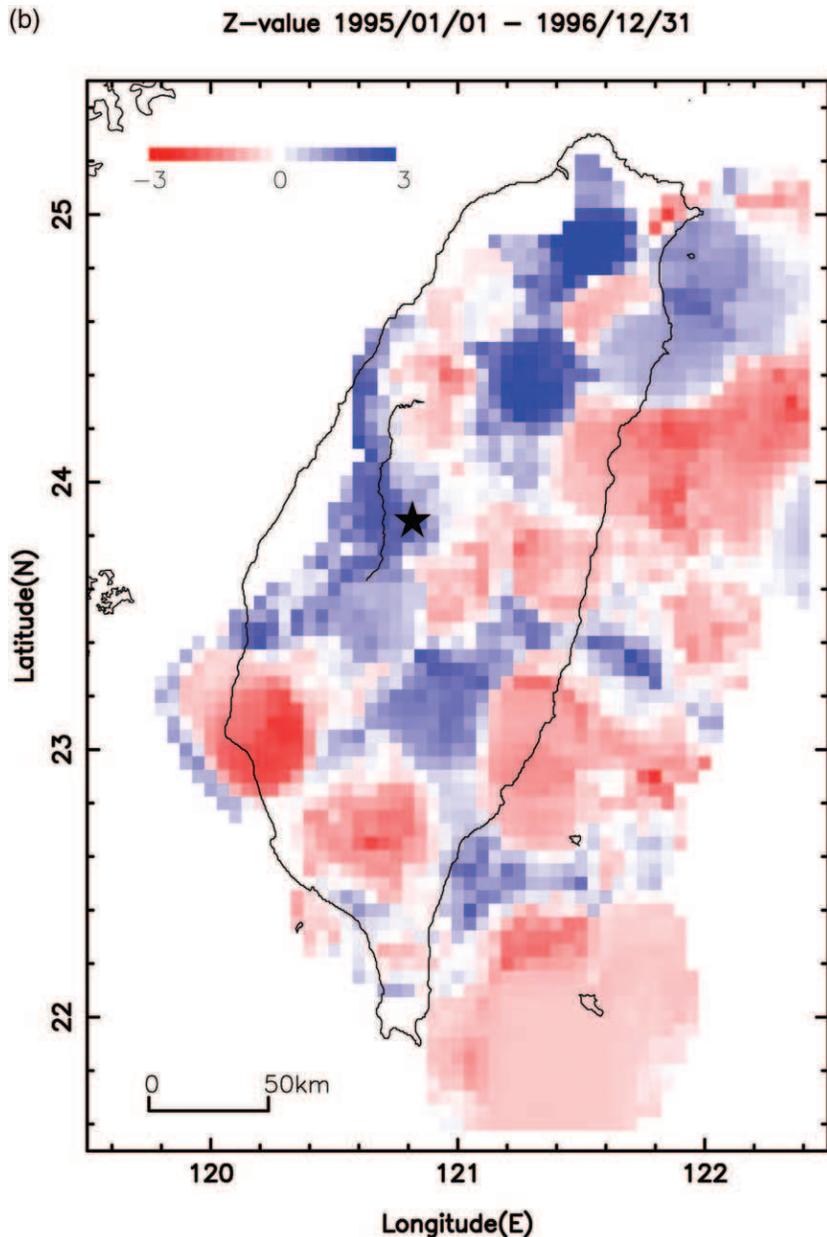


Figure 5. (a) Distribution of the Z-values from 1 January 1999 to 19 September 1999. Most of the Taiwan region is marked by the high positive Z-values that imply seismicity reduction. In contrast, areas surrounding the Chi-Chi earthquake source region have negative Z-values that imply increased activity prior to the main event. (continued)

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Figure 5. Continued. (b) Distribution of the Z-values from 1 January 1995 to 31 December 1996 suggests the background seismicity.



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