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Remotely triggered seismicity inferred from Taiwan regional catalog

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Abstract. The June 1992 Landers (California) earthquake triggered an increase in earthquake activity at distances up to 1250 km. It posed the question whether the remote triggering was really widespread in nature. To check this, we use the regional catalog of seismicity in Taiwan where twelve large $6.0 \leq M_D \leq 6.5$ seismic events took place over the last twenty years. We calculate the number of $M_D \geq 2.0$ earthquakes, as well as the number of $M_D \geq 4.5$ earthquakes, starting 15 days prior to and ending 15 days after each $M_D \geq 6.0$ event. The small-magnitude activity does not respond to the occurrence of a very large event. However, in 9 out of 12 cases, more $M_D \geq 4.5$ earthquakes occurred after a large event than in the same time interval before. The number of additional events is proportional to the size of the triggering earthquake. Thus, these extra events are possibly remotely triggered.

Introduction

The occurrence of earthquakes *remotely* triggered by other earthquakes or underground nuclear explosions has long been the subject of public speculation, while being denied by professionals at the same time. *Nikolayev and Vereshchagina* [1991] were, to our knowledge, the first to bring the problem to an attention of specialists. They showed that earthquakes may trigger other earthquakes in far-off areas. However, their findings remained largely questionable until further evidence appeared from the M_w 7.3 Landers earthquake [*Hill et al.*, 1993; *Anderson et al.*, 1994; *Bodin and Gomberg*, 1994]. The most promising explanation for the triggering observed was the effect of low-frequency seismic waves generated by the mainshock that disturbed the faults being near the failure threshold throughout a vast region. It was still unclear, though, whether the remote triggering was common in nature or was a rather exotic phenomenon. A retrospective look at existing seismicity catalogs may clarify this puzzle.

Method and Results

To check the hypothesis of remotely triggered seismicity, we use the regional earthquake catalog in Taiwan, where twelve large seismic events took place over the last twenty years. Taiwan is located in a complex tectonically active region with a high level of seismicity. The routine automated locating of earthquakes started in 1973, when the Taiwan Telemetered Seismic Network (TTSN) of approximately 25 stations went into operation [*Wang*, 1989] (Figure 1). During the period from 1973 to 1992, the network documented 92195 regional events with duration magnitudes $M_D \geq 2.0$. The magnitude cutoff in the catalog is about 1.5, and the catalog completeness threshold over the region shown in Figure 1 is about 2.0.

We identified the largest seismic events detected by the network over the past twenty years. There were twelve events with magnitudes $M_D \geq 6.0$, with epicenters shown in Figure 1 and other parameters summarized in Table 1. To compare the duration magnitudes employed in the TTSN catalog with the other estimates, the teleseismic body-wave magnitudes m_b from the Harvard catalog are also given in Table 1. We consider them better indicators of the earthquake size.

To quantify the possible triggered seismicity caused by each of the reference earthquakes, we consider the cumulative $M_D \geq 2.0$ regional seismicity starting 15 days prior to and ending at 15 days after each $M_D \geq 6.0$ event. The interval of 15 days is inferred from the maximum delay in the appearance of triggered events as reported from the studies of the Landers phenomenon. Note that the aftershocks of a big earthquake are related to the same causative fault and cannot be regarded as remotely triggered. Hence, for every $M_D \geq 6.0$ event, we define its "source exclusion zone", and all the earthquakes with epicenters in this zone are ignored in the cumulative seismicity calculation. As an additional characteristic, we separately count the number of moderate-size earthquakes with $M_D \geq 4.5$ occurring in the same 15-day intervals. Since all the $M_D \geq 6.0$ events took place offshore, their exact fault dimensions are unknown. Consequently, the source exclusion zone is defined here as a circle with a radius of 100 km around the epicenter of a big event, which covers the source area of an $M \sim 6$ earthquake with a sufficiently wide margin.

Figure 2 presents both cumulative regional seismicity curves and the occurrence of moderately-strong events ($M_D \geq 4.5$) for all twelve reference earthquakes. The time of the reference earthquake in the center of each plot is marked by a thick vertical line, with the duration magnitude and date indicated above. The thin vertical lines indicate the times of $M_D \geq 4.5$ earthquakes outside the source exclusion zone. The numbers above represent the magnitude and the epicentral distance from the reference event.

Examination of the plots reveals that the behavior of the overall cumulative seismicity is not affected by the $M_D \geq 6$ earthquakes, once its foreshock and aftershock activity has been excluded. In this sense, the Landers phenomenon, where the remotely triggered seismicity was essentially formed by the increased number of small events, has not recurred here. However,

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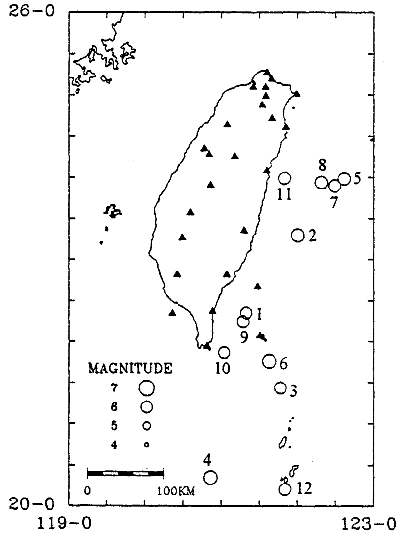

Figure 1. Map of Taiwan with the TTSN stations (triangles) and epicenters of the largest earthquakes (circles).

the number of $M_D \geq 4.5$ earthquakes is altered by the occurrence of a big event. The last three columns in Table 1 summarize their number before and after each reference event. In nine of the twelve cases, the number of $M_D \geq 4.5$ earthquakes recorded after the $M_D \geq 6.0$ shock exceeds the number of those occurring before it by 1 to 5. These additional moderate-sized events are not aftershocks, for the source exclusion zone is large enough to eliminate the effect of the aftershock activity on the observations.

By randomizing the data presented in Table 1, we can estimate the probability of the observed increase in seismicity occurring by random chance. From Table 1, we take a set of 24 numbers of earthquakes observed in 15-day periods (1, 4, 1, 3, 3, 1, etc.) and randomly reorder them into 12 "Earthquakes Before" and "Earthquakes After" pairs. We then determine, by doing this 10000 times, how often we find N sequences showing an increase (more events in the "Earthquakes after" pick) by chance. In this way, we find that 14 % of the time we can get $N \geq 7$, 5 % of the time we can get $N \geq 8$, and only 1 % of the time do we get 9 or more sequences with increases. Thus, we can reject the hypothesis that what we observe is purely random with about 99 % confidence.

The triggering potential of a seismic event, if real, should increase proportionally to its size. We check the validity of this assumption using the m_b magnitude as a measure of the earthquake size. The relationship between m_b and the increment in the number of moderate-sized events after the reference event is shown in Figure 3, together with its least-square linear approximation. There is a tendency for the number of triggered earthquakes to increase as the reference magnitude increases. The correlation coefficient is 0.55. Using the standard statistical graphs [*Bevington and Robinson*, 1992, Figure C.3], we find that the probability of randomly getting the correlation coefficient of at least 0.55 between uncorrelated variables for twelve observations is approximately 7 %. Thus, we can assert with about 93 % confidence that there exist a linear relationship between the increase in seismic activity and the reference event size. According to Figure 3, a magnitude threshold on triggering corresponds to the magnitude of about 5.6.

Because the overall positive correlation is strongly influenced by the M 6.7 event (number 9) which caused a largest increase in seismicity, it is important to check whether this increase was not caused by a coincidental factor such as the aftershocks of another earthquake. From Figure 2, we identify the only candidate for such a sequence, which is a series of five post-event 9 earthquakes occurring in nearly one day and having the magnitudes of 4.8, 5.0, 6.0, and 4.7 and the distances from the event 9 epicenter of 213, 352, 392, and 220 km. However, these earthquakes are distributed over a large area (the differences in epicentral distances of up to 179 km) and do not represent a clear foreshock-mainshock-aftershock pattern.

Discussion

Two main conclusions follow from this analysis. First, the remote small-magnitude activity does not seem to respond to the occurrence of a very large event. Second, there is a 75 % probability (9 cases out of 12) that there will be 1 to 5 more moder-

Table 1. Large Earthquakes Used in This Study

Event no.	Date	Origin time (GMT)	Coordinates Lat.(°)	Long.(°)	Depth (km)	M_D*	m_b*	Earthqks before†	Earthqks after‡	Diff.§
1	23 Jul 78	14:42	22.35	121.33	17	6.0	6.5	1	4	+3
2	23 Dec 78	11:23	23.30	122.00	33	6.3	6.6	1	3	+2
3	2 Oct 80	19:07	21.87	121.78	33	6.0	5.5	3	1	-2
4	19 Apr 82	14:42	20.35	120.86	36	6.5	5.8	0	3	+3
5	24 Jun 83	09:06	23.98	122.61	54	6.2	6.0	2	3	+1
6	2 Aug 83	02:18	21.76	121.63	156	6.5	6.1	1	3	+2
7	7 Sep 83	23:11	23.90	122.49	33	6.1	5.5	0	0	0
8	21 Sep 83	19:20	23.94	122.32	33	6.2	6.0	0	1	+1
9	5 Mar 84	03:36	22.24	121.29	651	6.1	6.7	2	7	+5
10	23 Apr 85	16:16	21.87	121.04	181	6.0	6.4	0	2	+2
11	14 Nov 86	21:20	23.99	121.83	33	6.1	6.2	3	1	-2
12	4 Dec 88	06:14	20.21	121.84	33	6.1	5.6	0	2	+2

* M_D is the duration magnitude; m_b is the body-wave magnitude.

† Number of earthquakes with $M_D \geq 4.5$ outside source exclusion zone within 15 days before the big event.

‡ Number of earthquakes with $M_D \geq 4.5$ outside source exclusion zone within 15 days after the big event.

§ Difference between the number of earthquakes with $M_D \geq 4.5$ after and before the big event.

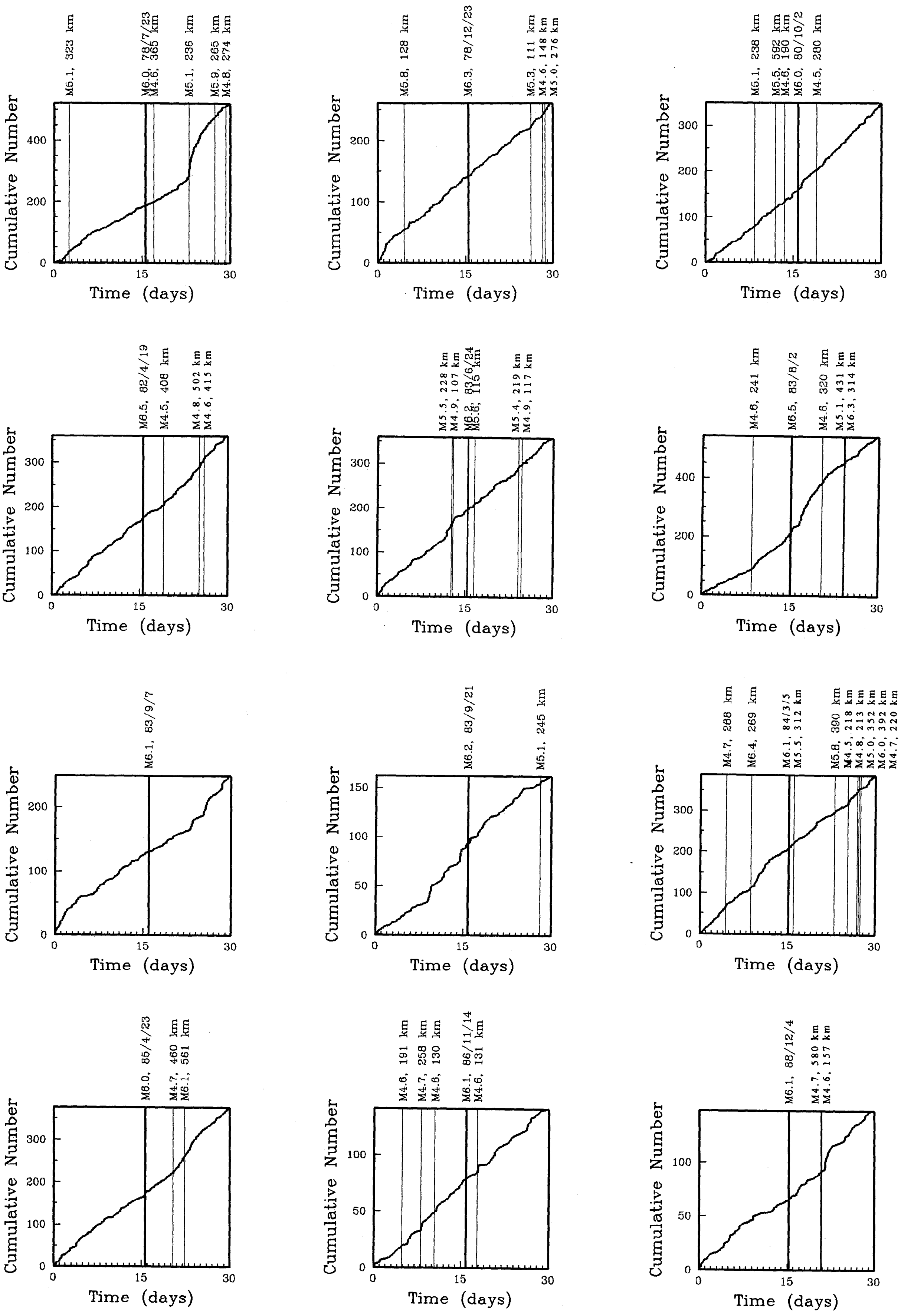

Figure 2. Seismicity in the 15 days before and 15 days after each reference earthquake.

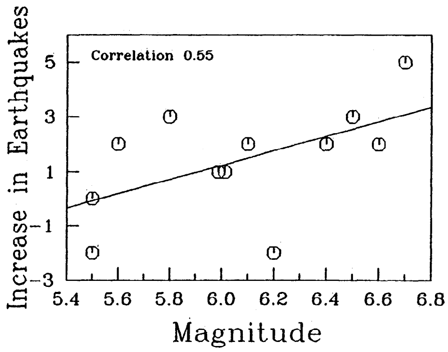

Figure 3. The relationship between the increase in the number of moderate-sized earthquakes following the big event and its teleseismic body-wave magnitude.

ate-size (M ≥ 4.5) earthquakes after the large event than before it. This suggests that some of these extra events could be remotely triggered, i.e., that the big earthquakes are capable of stimulating the seismic activity at distances many times longer than their source dimensions. An additional piece of evidence in favor of this conclusion is that a proportionality is observed between the number of triggered events and the size of the reference earthquake.

In the above analysis of seismicity, a 15-day time window was chosen. The number of the reference events that caused increased moderate-magnitude activity was not changed by increasing the window from 15 to 25 days. There are natural constraints to keep this window length within reasonable bounds. The recurrence rate of M ≥ 4.5 earthquakes makes it impractical to use smaller windows. On the other hand, if the window increases to a month or more, the causal relationship between the late occurring earthquakes and the reference event is lost.

This study reveals that only earthquakes with sufficiently large magnitudes can be triggered. This disagrees with what was observed after the Landers earthquake. The Landers mainshock had a Harvard body-wave magnitude m_b=6.2. If any comparison can be made with the Taiwan data in Figure 3, an earthquake with this magnitude could trigger 1 to 2 M ≥ 4.5 earthquakes. The only earthquake of this size known as remotely triggered by Landers is the Little Skull Mountain event in Nevada. In this sense, our results do not contradict the Landers experience.

The work described above focused on the triggering effect of the strongest local earthquakes in Taiwan. In a companion paper (K.-L. Wen, I. Beresnev, and S.-N. Cheng, Moderate-magnitude seismicity remotely triggered in Taiwan region by largest earthquakes around the Philippine Sea plate, submitted to the Bull. Seism. Soc. Am., 1995), we conduct the similar investigation of the triggering effect of the largest earthquakes in the entire Western Pacific region. From the IRIS Preliminary Determination of Epicenters catalog, we located twelve earthquakes with $m_b \geq 6.5$ (a mere coincidence with the number of Taiwan reference events), with the epicenters ranging from 130 to 3000 km. Nine of them caused an increase in $M_D \geq 4.5$ seismicity in Taiwan in the 15-day intervals, and ten showed an increase in $M_D \geq 4.0$ seismicity. Thus, we found a remarkable agreement with the results of the present paper.

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