Tidal triggering of earthquakes precursory to the recent Sumatra megathrust earthquakes of 26 December 2004 ($M_w$ 9.0), 28 March 2005 ($M_w$ 8.6), and 12 September 2007 ($M_w$ 8.5)

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Abstract

[1] I observed tidal triggering of earthquakes precursory to the three giant earthquakes occurring off Sumatra on 26 December 2004 ($M_w$ 9.0), 28 March 2005 ($M_w$ 8.6), and 12 September 2007 ($M_w$ 8.5). I measured the correlation between the Earth tide and earthquake occurrence in and around the focal regions of these megathrust earthquakes. The result of statistical analysis indicates that a high correlation appeared for several to ten years preceding the occurrence of the large earthquakes. The correlation vanished after the main events. The frequency distribution of tidal phase angles in the pre-event period exhibited a peak near the angle where the tidal shear stress is at its maximum to accelerate the fault slip. This implies that the high correlation observed in the pre-seismic stage is not a stochastic chance but is likely a physical consequence of the tidal stress change.

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1. Introduction

[2] The Earth tide produces cyclic stress variations in the Earth. These stress variations, of the order of $10^3 \sim 10^4$ Pa, are much smaller than typical stress drops of earthquakes, but their rates are often larger than those of tectonic stress accumulation. Thus the tidal stress might be expected to trigger an earthquake, and many searches have been carried out for the correlation between the Earth tide and earthquake occurrence [e.g., Emter, 1997]. Although most have reported negative conclusions [e.g., Schuster, 1897; Heaton, 1982; Vidale et al., 1998], many recent studies have shown a positive correlation for microearthquake swarms [Wilcock, 2001; Tolstoy et al., 2002; Stroup et al., 2007], regional seismic events [Tanaka et al., 2002a, 2004], and even globally distributed earthquakes [Tanaka et al., 2002b; Cochran et al., 2004].

[3] A topic of interest in the recent investigation is a precursory pattern observed in the spatiotemporal distributions of the earthquake-tide correlation. A study on the Tonga subduction zone has indicated that a high correlation was detected only in the several years prior to the 1982 $M_w$ 7.5 South Tonga earthquake in and around the future rupture area of the large event [Tanaka et al., 2002a]. Similar space-time characteristics have been reported for several large earthquakes in China and California [Yin et al., 1995, 2000]. These results suggest that tidal triggering may appear only when the stress in the focal region is close to a critical
condition to release a large rupture. However, relevant studies are still quite limited, and it is not clear yet whether the phenomenon is universally observed.

[4] In the present study, I examine the correlation between the Earth tide and earthquake occurrence in the focal region of the recent catastrophic earthquake occurring off northern Sumatra on 26 December 2004 ($M_w 9.0$). I focus on the spatio-temporal variation of the earthquake-tide correlation to detect a possible precursory anomaly prior to this giant earthquake. After the 2004 event, the Sunda megathrust ruptured again on 28 March 2005 and 12 September 2007, which generated other great earthquakes of $M_w 8.6$ and 8.5, respectively. I also consider whether these two events display premonitory tidal triggering.

2. Data

Figure 1. Epicenters of the 2004 Sumatra-Andaman, 2005 Nias, and 2007 Southern Sumatra earthquakes (stars) and corresponding study areas (solid rectangles). Focal mechanism solutions of these earthquakes are shown after the Global CMT catalog. Black dots are the epicenters of shallow earthquakes (focal depth $< 70$ km, $M_w \geq 5.0$) for the period from 1976 to 2008.

[5] Off the west coast of Sumatra, the three largest earthquakes of the past four decades occurred along the subduction plate boundary between the Indo-Australia and Eurasia plates on 26 December 2004 (Sumatra-Andaman, $M_w 9.0$), 28 March 2005 (Nias, $M_w 8.6$), and 12 September 2007 (Southern Sumatra, $M_w 8.5$). I investigate the correlation between the Earth tide and earthquake occurrence in and around the focal regions of these megathrust earthquakes. For each event, I define the study area as a rectangular area which covers its aftershock zone. The epicenters of the main events and the corresponding study areas are shown by stars and solid rectangles, respectively, in Figure 1. The size of the areas is 1500 km $\times$ 500 km for the 2004 event, and 400 km $\times$ 300 km for the 2005 and 2007 events. To measure the correlation, I use the origin times, hypocenter locations, and focal mechanism solutions of shallow earthquakes (focal depth $< 70$ km, $M_w \geq 5.0$), which are listed in the Global Centroid Moment Tensor (CMT) catalog for the period from 1976 to 2008. The epicenters of these events are also shown by black dots in Figure 1. A total of 1126 earthquakes are used in this study.

3. Method

[6] I statistically investigate the correlation between the Earth tide and earthquake occurrence following the procedure of Tanaka et al. [2002a, 2002b]. I theoretically calculate the Earth tide at the hypocenter of each event for the Preliminary Reference Earth Model [Dziewonski and Anderson, 1981]. This calculation includes both the direct solid Earth tide and the indirect term due to the ocean tide loading for the ocean tide model NAO.99b [Matsumoto et al., 2000; Takanezawa et al., 2001] (see Tanaka et al. [2002b] for the details of the Earth tide calculation). As for the tidal component, I only consider the shear stress change along the slip direction on the fault plane (positive in the same sense as the fault slip). I do not use the normal stress in this study because it is difficult to identify the fault plane from the two nodal planes. The normal stress changes on the two nodal planes are often not in phase, so that improper selection may lead to erroneous conclusions. The shear stress, on the other hand, does not depend on the selection of the fault plane due to the symmetry of the stress tensor.

[7] From the calculated tidal shear stress, I assign the tidal phase angle at the occurrence time for each earthquake. The tidal phase angle, taking a value between $-180^\circ$ and $180^\circ$, is assigned
by linearly dividing the time interval from $-180^\circ$ to $0^\circ$ or from $0^\circ$ to $180^\circ$, where $0^\circ$ and $\pm 180^\circ$ correspond to the maximum and the minimum of the tidal shear stress in the slip direction, respectively. Determining the phase angles for all the earthquakes, I statistically test whether they concentrate near some particular angle or not by using the Schuster's test [e.g., Emter, 1997]. In this test, the result is evaluated by $p$-value. The $p$-value, ranging between 0 and 1, represents the significance level to reject the null hypothesis that the earthquakes occur randomly irrespective of the tidal phase angle. A smaller $p$-value indicates a higher correlation between the Earth tide and earthquake occurrence.

4. Results

Figure 2. (a) Temporal variation of $p$-value in the area of the Sumatra-Andaman earthquake. A time window of 3000 days, which is represented by horizontal bar, is shifted by 500 days. (b) Frequency distribution of tidal phase angles in the 3000 days prior to the Sumatra-Andaman earthquake. Solid curve represents a sinusoidal function fitted to the distribution.

[8] Figure 2a shows the temporal variation of $p$-value in the area of the 2004 Sumatra-Andaman earthquake. A time window of 3000 days, which is selected to secure sufficient number of earthquakes (>10) for statistical analysis [Schuster, 1897], is shifted by 500 days. The $p$-value had been larger than 40% for about 20 years since 1976. However, a clear decrease appeared in the late 1990s. The $p$-value decreased until the occurrence of the Sumatra-Andaman event and attained a significantly small value of 3.6% just prior to it. Figure 2b shows the frequency distribution of tidal phase angles for the period of 3000 days prior to the Sumatra-Andaman event. The phase distribution in this period had a peak near the angle $0^\circ$, where the tidal shear stress is at its maximum to accelerate the fault slip. This implies that the observed small $p$-value is not a stochastic chance but is likely a physical consequence of the tidal stress change. After the Sumatra-Andaman event, the $p$-value returned to a high level (11%) and the phase selectivity disappeared.

Figure 3. Spatial distribution of $p$-value in the 3000 days prior to the Sumatra-Andaman earthquake. A spatial window of 500 km, which is represented by horizontal bar, is shifted by 200 km from SSE to NNW.

[9] In the pre-seismic low-$p$ period, I further investigate the spatial distribution of $p$-value. The result is shown in Figure 3, where a spatial window of 500 km in the SSE–NNW direction is shifted by 200 km. We see that a small $p$-value appeared only in the southern part of the study area, which includes the initial rupture point of the Sumatra-Andaman earthquake. This suggests that a precursory strong tidal correlation concentrated in the area around the nucleation zone of the impending great rupture.

Figure 4. (left) Temporal variation of $p$-value in the area of the (a) Nias and (c) Southern Sumatra earthquakes. A time window of 6000 days (for the period from 1976 to 1997 in Figure 4a) and 3000 days (for the other periods), which is represented by horizontal bar, is shifted by 500 days. (right) Frequency distribution of tidal phase angles in the 3000 days prior to the (b) Nias and (d) Southern Sumatra earthquakes. Solid curve represents a sinusoidal function fitted to the distribution.
A precursory decrease of $p$-value was also found for the 2005 Nias, and 2007 Southern Sumatra earthquakes. Figure 4a shows the temporal variation of $p$-value in the area of the 2005 Nias earthquake. Due to a limited number of earthquakes, a longer time window of 6000 days is used for the first about 20 years. We find that the pattern of $p$-value change is similar to the Sumatra-Andaman case; the $p$-value was large in the early years of the investigation period, but a clear decrease appeared preceding the occurrence of the Nias earthquake. The minimum value attained just prior to the event was as small as 0.71%. The phase distribution in the pre-seismic period also showed a similar feature to that for the Sumatra-Andaman earthquake; the histogram exhibited a peak near the angle 0° (Figure 4b). Figure 4c shows the $p$-value change for the 2007 Southern Sumatra earthquake. A precursory drop of $p$-value also appeared for this event, although the minimum value just prior to the event was 6.4%, which was not small enough to judge a significant correlation ($p < 5\%$ is often considered as the threshold of statistical significance). However, the phase angles in the pre-event period again concentrated near the angle 0° (Figure 4d), which suggests that a premonitory tidal effect also existed prior to the Southern Sumatra earthquake although the statistical significance was not high enough.

5. Discussion and Conclusions

In this study, I observed a correlation between the Earth tide and earthquake occurrence precursory to the three megathrust earthquakes occurring off Sumatra on 26 December 2004, 28 March 2005, and 12 September 2007. The results I obtained indicate that a strong tidal effect appeared for several to ten years preceding the occurrence of the $M_w = 8.5–9.0$ earthquakes. In the pre-seismic periods, the tidal phase angles distributed with a peak near the angle 0° where the tidal stress change is at its maximum to promote the fault slip; more earthquakes occurred during the tidal phase range between $-90^\circ$ and $90^\circ$ (the period of encouraging stress) than during the other half of the tidal cycle. This indicates that the observed high correlation is not coincidental. To further test the significance of these observations, I perform a simple binomial test [Cochran et al., 2004] for the periods of 3000 days prior to the occurrence of the main events. If earthquakes occur randomly, the number of events with a tidal phase angle between $-90^\circ$ and $90^\circ$ should be equal to that in the other half of the tidal phase range. This binomial test also shows a significant deviation from random earthquake occurrence in the pre-event periods; the probabilities of obtaining the observed results (Figures 2b, 4b, and 4d) from a binomial model are 4.1%, 1.4%, and 0.80%, respectively. For the case of the Sumatra-Andaman earthquake, I further confirmed that a premonitory high correlation was restricted to the area where the imminent earthquake rupture initiated.

Some studies reported other precursory signals in the seismicity prior to the 2004 Sumatra-Andaman earthquake. Jiang and Wu [2005] found that the average moment tensor in the surrounding area was similar to the focal mechanism of the Sumatra-Andaman event for about ten years before this great earthquake. Prior to this time period, mechanisms showed different patterns. Nuannin et al. [2005] detected a statistically significant low-$b$ region around the epicenter of the Sumatra-Andaman event using a five-year catalog prior to the event. This low-$b$ region extended about 450 km along the trench, which is roughly coincident with the pre-shock tidally-correlated area observed in this study (Figure 3). In almost the same region, Mignan et al. [2006] identified a clear Accelerated Moment Release (AMR) behavior at a level of statistical significance. My study suggests that monitoring of tidal triggering may be an additional factor to reveal pre-seismic anomalous areas where giant earthquakes are impending.

The tidal influence on the initiation of giant earthquakes themselves is also an interesting issue to be explored. The tidal phase angles of the mainshocks considered in this study are 35°, 77°, and $-10^\circ$ for the Sumatra-Andaman, Nias, and Southern Sumatra earthquakes, respectively. It is worth noting that all the three events occurred during the period of encouraging stress (the tidal phase range between $-90^\circ$ and $90^\circ$), although this is not statistically significant.
For the physical mechanism of tidal triggering, we need more detailed studies in view of laboratory-driven friction laws [e.g., Dieterich, 1979; Ruina, 1983]. A recent theoretical study based on the rate- and state-dependent friction law predicted that earthquake triggering due to dynamic stress oscillation is possible when the fault is at the end of the earthquake cycle [Perfettini et al., 2003]. This prediction appears to be consistent with my finding. On the other hand, the amplitude of the tidal stress is much smaller than the threshold for triggering detection which was derived from laboratory experiments [Lockner and Beeler, 1999; Beeler and Lockner, 2003] and observations of static and/or dynamic triggering [King et al., 1994; Gomberg et al., 2001]. New evidence presented in this study that much smaller stress change can trigger an earthquake may provide a new insight for elucidating the physical mechanism of earthquake triggering.

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