Tidal Synchronicity of the 26 December 2004 Sumatran Earthquake and its Aftershocks

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Abstract

The incidence of earthquakes along the entire Andaman/Sunda/Java Trench plate boundary region has been investigated for the period 01 November 2004 onwards, encompassing the 26 December 2004 earthquake. The frequency of earthquake-incidence during this period correlates with the cyclic variations in tidal forces: maximum earthquake activity occurs around the time of full and new moons, typically lagging by *ca*. 3 days. Furthermore, for the period 01 November 2004 onwards, on average, (a) half of all earthquakes occur in the 4-day periods about this lag and, (b) half of magnitude-5 and greater earthquakes occur in the 3.3-day periods about this lag.

Index Terms.

Fourier analysis. Time series analysis. Tidal forces. Plate motions: present and recent. Earthquake interaction, forecasting, and prediction.

Earthquake triggering. Tidal loading. Sumatra.

Introduction

Earthquakes of similar magnitude to the 26 December 2004 earthquake are rare. Other examples include the magnitude-8.6 Alaskan earthquake of 1964 (Krauskopf, 1972) and the magnitude-7.9 event near Enggano on the south-east end of the Sumatran forearc in 2000 (Milsom, 2005). Such very large earthquakes are associated with subduction zones where two tectonic plates converge, with one plate of heavier oceanic crust being subducted below one of lighter continental crust (Bolt, 2004). They usually occur as a result of shallow thrust events beneath the forearc. However, Milsom (2005) points out that due to the presence of the Burma Plate (a plate between the Indian Ocean and SE Asian plates, triangular in cross-section and much longer than it is wide; referred to by Curray (1989) as a sliver plate), Sumatran earthquakes cannot be understood merely as the simple product of two major plates interacting (see Barber *et al*, 2005, p1). The Sumatran-Andaman subduction system, which extends more than 2000km from Burma to the Sunda Strait, forms the western part of the Sunda Arc (Milsom, 2005). Near this plate boundary, as a result of the 26 December earthquake, the seafloor rose by up to 15m, whereas landward of this boundary it subsided (Teeuw, 2005). In the 1964 Alaskan earthquake there were areas of uplift (more than 16m at the sea floor) and regions of subsidence (on the order of 2-3m) (Krauskopf, 1972).

Such earthquakes cause ruptures that release stress along the subduction plate boundary (Keller, 1996; Bolt, 2004). The 26 December earthquake caused a 450km rupture along the subduction zone off northern Sumatra, with aftershocks active over a 1300km section from the Andaman Islands to the earthquake epicenter near northern Sumatra (Cummins and Leonard, 2005). The earthquake hypocenter was at a depth of 30km below mean sea level at the extreme western end of the Ring of Fire, the earthquake belt that accounts for around 80% of the world's largest earthquakes. According to Cummins and Leonard (2005) the rupture in question was probably due to an initially rapid slip that became less rapid as it propagated northwards. Milsom (2005) suggests that the slip was initiated beneath the forearc basin near the Mentawi Fault, propagating towards the trench.

According to Khan *et al* (1990) there have been approximately 3.5 million deaths in 38 major earthquakes between 342 and 1976AD. Keller (1996) highlighted that 'our modern society is very vulnerable to catastrophic loss from large earthquakes' with many high-risk areas being highly populated. The desire to predict such earthquakes so that loss of life can be reduced has led to significant interest in the literature on identifying precursors to predict earthquakes, such as the velocity of P-wave changes, ground tilt and uplift, decreases in electrical resistivity of rocks, underground water level fluctuations and increases in radon emissions (Bolt, 2004).

This paper examines if observations of tidal synchronicity can assist in the prediction of earthquakes. This approach developed because during the period in which the 26 December 2004 earthquake and its aftershocks occurred, the Radon Research Group at the University of Northampton in the UK were compiling hourly time-series of radon data as part of ongoing investigations into (a) radon anomalies associated with UK earthquakes (Crockett *et al*, 2005) and (b) tidal influences on atmospheric radon levels (Groves-Kirkby *et al*, 2005). It should be noted at this point that periods of maximum tidal force occur at full and new moons and that:

i) the three UK earthquakes (*ca*. 4-10km depth) considered in (a) above occurred in close relation to full moons and;

ii) the 26 December earthquake and its principal aftershocks (*ca*. 20-30km depth) occurred in close relation to full and new moons.

Following this observation of apparent tidal synchronicity in earthquakes, a preliminary investigation was undertaken to assess the extent of any tidal synchronicity in the incidence of earthquakes in the Andaman/Sunda/Java Trench region. No radon anomalies associated with these Sumatran earthquakes were detected in the UK radon data, although tidal cycles were observed and these are considered in a separate paper (Crockett *et al*, submitted to Geophys. Res. Lett.).

Earthquake Frequencies and Statistical Analysis

Earthquake data for the entire Andaman/Sunda/Java Trench plate boundary region, from the Andaman Islands in the north to Irian Jaya in the east, for the period 01 January 2004 to 12 June 2005 were downloaded from the Advanced National Seismic System on-line database (www.anss.org) on 01 July 2005.

Initially, the daily frequency distribution of earthquake incidence along the entire length of the trench was established. The region was relatively quiet until mid-November 2004. The frequency distribution for 01 November 2004 onwards is shown in Figure 1, with the lunar phase superimposed as a sinusoidal curve for reference. There were 5196 recorded earthquakes (in the database) during this period, 768 of these were magnitude-5 or greater (M5+) and have a similar frequency distribution. Spatial analysis indicates that the earthquake activity occurs in two distinct geographical areas. The activity prior to 26 December 2004 occurs predominantly at the Pacific end of the plate-boundary, the remainder of the activity occurs predominantly off the Northern end of Sumatra, the two areas being some 5000km apart along the arc of the Sunda/Java Trench.

The initial Pacific-end activity occurred in two main episodes. The first started on 11 November (new moon on 12 November) with a magnitude-7.5 earthquake in the Banda Sea, and the second starting on 26 November (full moon) with a magnitude-7.1 earthquake at the northern end of Irian Jaya. This second period of activity, although occurring in the region of the Sunda/Java trench, is possibly associated with movement along the adjoining plate-boundary between the Philippine/Pacific and Eurasian plates.

The subsequent near-Sumatra activity on and following 26 December occurs in four distinct episodes: (i) the great earthquake of 26 December (full moon) and its most significant aftershocks of (ii) 24 January (magnitude-6.3, full moon on 25 January), (iii) 28 March (magnitude-8.7, full moon on 25 March) and (iv) 10 April (magnitude-6.7, new moon on 08 April), and the lesser aftershocks associated with them.

The cross-correlation between the frequency distribution and the modeled variation in tidal force is shown in Figure 2, which also shows the cross-correlation for the northern Sunda-trench region for the period 12 December 2004 (new moon) to 12 June 2005. Both the correlations peak at values of 0.2-0.25, both positive and negative. Conventionally, this magnitude of correlation coefficient would be regarded as being of borderline statistical significance but the cyclic behavior is highly significant. The magnitude of the correlation coefficient is a measure of the similarity of the ‘shapes’ of the tidal-force and earthquake frequency distributions: the cyclic behavior with its period of 14-15 days indicates that this period is present in both the tidal-force (known) and earthquake-frequency data (under investigation). It is also clear from Figure 2 that the correlation coefficient peaks at 3-4 days following the peak tidal force, i.e. the earthquake-incidence maxima occur 3-4 days after full or new moons.

The presence of periodic behavior in the earthquake-incidence is confirmed by Fourier analysis. Figure 3 shows two Fourier spectra for earthquake incidence for the northern Sunda Trench region for the period 12 December 2004 to 12 June 2005. One spectrum is for all recorded earthquakes, the other is for M5+ earthquakes. Both spectra show clear components at 15.2 and 30.4 days: within the resolution of the discrete Fourier transforms on the two data-sets, these components correspond to the tidal-strength (14-15 days) and lunar (29-30 days) periods. These components are larger for the M5+ earthquakes indicating that the tidal effects are more significant on these bigger earthquakes. The component at 10.7 days corresponds to the frequency sum of the 15.2-day and 30.4-day components: the frequency difference is 30.4 days also, and so is not separately visible in the spectra. The 91.1-day components in the spectra arise because of the 92-day period between the two great earthquakes of 26 December 2004 and 28 March 2005 and the large numbers of associated aftershocks.

Figure 4 shows a cumulative cyclic correlogram of earthquake incidence and was constructed using a variant of 'base-number correlation', a novel statistical technique (Crockett *et al*, 2004). In this analysis, the equal-phase frequency distribution of earthquakes is established with 60 equal-phase intervals per lunar month, i.e. each interval averaging *ca*. 12 hours over all lunar months. A typical cumulative lunar month comprising 60 equal-phase intervals is then constructed by summing the corresponding earthquake frequencies from the frequency distribution. This cumulative lunar month is then plotted in a polar-plot to fully show the cyclic nature of the earthquake incidence: the lengths of the 60 radial arms are proportional to the cumulative frequencies and their angular positions (anticlockwise) correspond to the phase within the lunar month. The outer and inner circles indicate the mean frequency plus or minus two standard deviations, i.e. approximately the 95% confidence interval, and give an indication of the expected frequencies.

Figure 4 shows frequency maxima much greater than the outer/upper confidence limit, centered at 3-4 days lagging full and new moons, particularly full moons. This confirms both the tidally-periodic nature of earthquake incidence and the typical duration of the lag following full and new moons. Further analysis reveals that half of all earthquakes occur in the 4-day periods centered on these maxima (i.e. 4 days per *ca*. 15-day tidal period). Repeating the analysis for M5+ earthquakes reveals that half of these earthquakes occur in the 3.3-day periods centered on these maxima (i.e. 3.3 days per *ca*. 15-day tidal period). This shorter period agrees with the bigger frequency components present in the M5+ Fourier spectrum.

Whilst the data-analysis was in progress, there was a magnitude-7.2 earthquake on 24 July 2005 close to the Nicobar Islands at the northern end of the plate boundary. This occurred 3 days and a few hours after the full-moon of 21 July. This lag is in full agreement with the lag revealed by the correlations shown in Figures 2 and 4, providing further evidence supporting the presence of a tidal influence on earthquake incidence in this region.

Possible Mechanisms

The tidal-force has two basic influences on the stresses in the Earth's crust. First, there is the direct tidal attraction: the tidal force between the rocks in the Earth's crust and the moon or the sun, i.e. (solid or bodily) Earth tides (e.g. Lowrie, 1997). Second, there is (ocean) tidal loading (e.g. Baker, 1984; Farrell, 1972): the tidal movement of water which cyclically loads and unloads regions of the Earth's crust. In either case, or in the case of a combination of the two influences, the net effect is that the Earth's crust is cyclically stretched and compressed with a basic 12.4-hour lunar-tidal period and that the magnitude of this effect is cyclically modulated with a *ca*. 14-15-day cycle (i.e. spring tide to spring tide) arising from the interaction of the lunar and solar tides. In addition, owing to the slight asymmetry in the tidal forces associated with the new and full moons (the gravitational and centrifugal components do not exactly match), there is a *ca*. 30-day tidal-cycle (i.e. full moon to full moon or new moon to new moon). There are also longer-period cycles in the tidal force owing to varying orbital relationships between the three bodies within the solar system. Last, there can be local/regional variations in ocean tides, dependent on coastal, island or peninsular configurations, which can affect the basic 12.4-hour tidal-loading cycle.

These relationships suggest that cyclical crustal flexing, which will be at a maximum at full or new moons, might provide sufficient extra force to a plate-boundary region already on the point of rupture to trigger an earthquake that was 'waiting to happen'.

Conclusion

Correlation between the incidence of earthquakes in the Sunda-Java Trench region and lunar/tidal phases has been observed and quantified and found to be significant. The incidence of earthquakes is largest *ca*. 3-4 days after a full or new moon, particularly the full moon. On average, since 01 November 2004:

i) half of all earthquakes occurred in the 4-day periods 1-5 days after the new/full moons;

ii) half of M5+ earthquakes 3.3-day periods 1.35-4.65 days after the new/full moons.

Although causality appears intuitively reasonable, at the present time possible mechanisms await detailed investigation. Very preliminary investigation has revealed evidence of tidal synchronicity in other seismically-active areas including, for example, the Tonga Trench and sections of the western seaboards of North and South America.

Notwithstanding, and noting the predictions by McCloskey *et al* in their recent papers (McCloskey *et al*, 2005; Nalbant *et al*, 2005), we would suggest that the 'big' earthquake that they predict – or its main aftershocks – will probably occur at or just after a full or new moon although at present we have no way of predicting any timescale for this. In essence, this analysis leads to the suspicion that the tidal effects in this region and perhaps elsewhere may serve to trigger the 'big' earthquake(s) that may be 'waiting to happen'.

Also, as observed above, during the preparation of this paper there was a magnitude-7.2 earthquake 24 July 2005 close to the Nicobar Islands. The lag of 3 days and a few hours after the preceding full-moon is in full agreement with the lag revealed by the cross-correlations and in accordance with the foregoing prediction.

At a practical level, knowledge that the probability of (big) earthquakes is higher at certain times than at others may enable medical and other authorities to be more responsive at those times of higher probability by, for example, placing emergency services on a higher state of readiness or preferentially scheduling elective medical treatments at times of lower probability.

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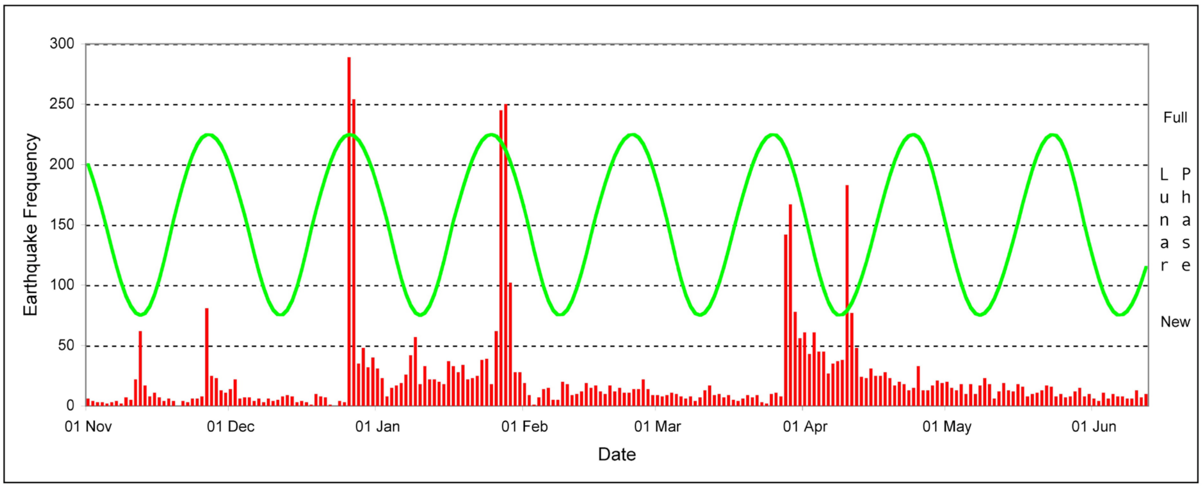
Figure 1. Daily Frequency Distribution of Earthquakes Along the Andaman/Sunda/Java Trench, 01 November 2004 – 12 June 2005.

Figure 2. Cross-Correlation of Tidal Forces and Earthquake Incidence.

Figure 3. Fourier Spectrum of Earthquake Incidence, Sunda Trench, 12 December 2004 – 12 June 2005.

Figure 4. Cumulative Cyclic Correlation of Earthquake Incidence with Lunar Phase, 12 December 2004 – 12 June 2005.



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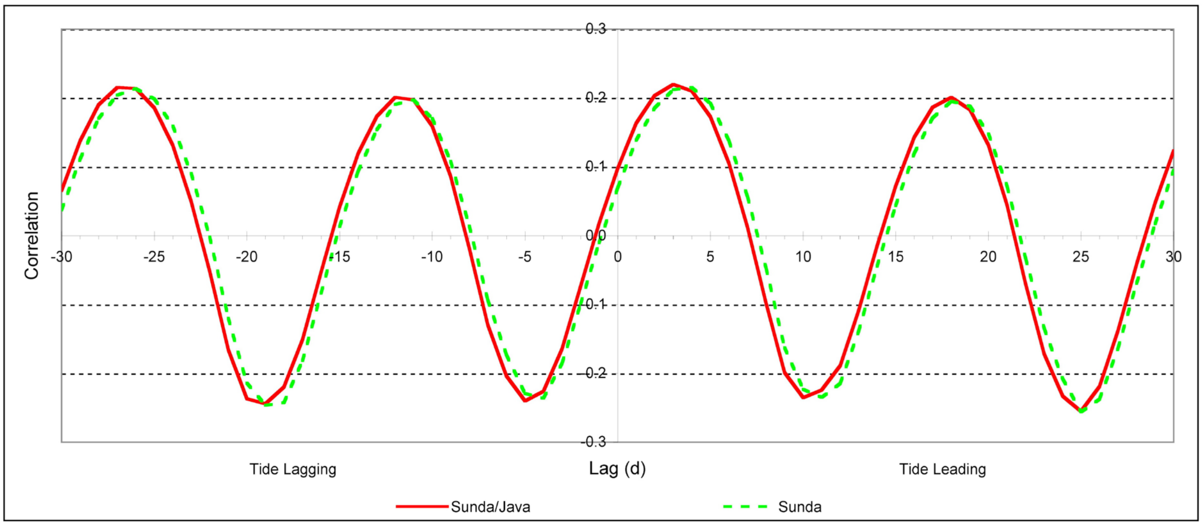

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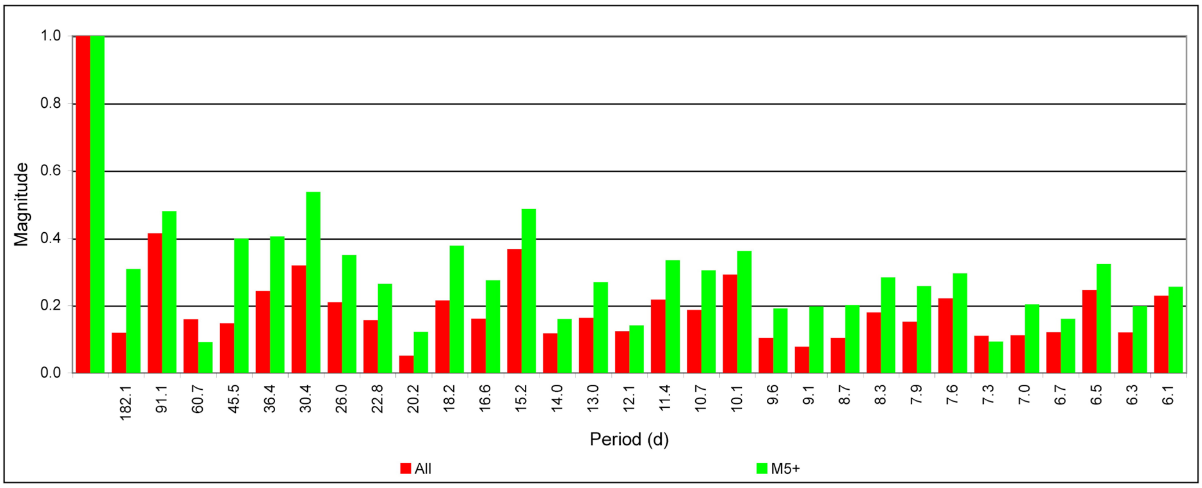

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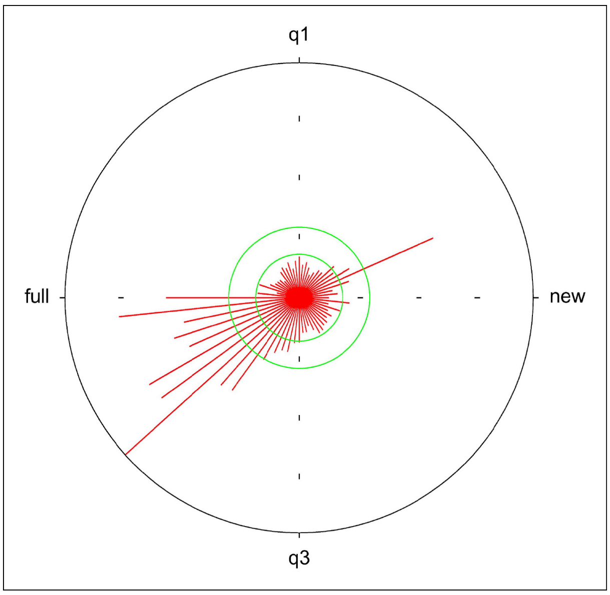

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