Were the 26 December 2004 Sumatran Earthquake and tsunami tidally triggered?

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Abstract

This paper describes observation and quantification of tidally synchronous earthquake incidence in the period around the 26 December 2004 Sumatran earthquake/tsunami event. In addition, three other recent catalogued Indonesian earthquake/tsunami events are examined, as is the 01 April 2007 Solomon Islands event which occurred during the preparation of this paper.

For the 26 December 2004 event, the relationship indicates earthquake inducement via ocean tidal loading and, during the ten-month period of high earthquake activity in this region, earthquake incidence associated with tidal-loading maxima was (a) 38% and (b) 86% higher than the period averages for the full and declustered earthquake catalogues respectively. A preliminary investigation of the Solomon Islands event indicates a similar relationship, although the inducement appears to be via earth tides in this case, and incidence associated with earth-tide maxima in this region was (a) 70% and (b) 50% higher than the period averages for the full and declustered major-earthquake catalogues respectively. It is concluded that the 26 December 2004 earthquake/tsunami event was tidally triggered, and the 01 April 2007 Solomon Islands also on the basis of the preliminary investigation, but that the three other Indonesian events investigated were not, with two of these displaying no tidal influence.

1. Introduction

This paper focuses on the statistical significance of tidal synchronicity of the 26 December 2004 earthquake (Mw=9.0) and subsequent major aftershocks along the Sunda Trench plate-boundary region. This earthquake triggered the largest tsunami since 1900, the deadliest in recorded history which killed up to 230,000 people (www.tsunamispecialenvoy.org/country/humantoll.asp). The paper also examines the significance of tidal synchronicity of three other recent earthquake/tsunami events in this region, *i.e.* 12 December 1992 (Ms=7.5), 02 June 1994 (Ms=7.2) and 08 October 1994 (Ms=6.8). Although these were smaller than the 26 December 2004 earthquake, and triggered smaller tsunamis, several thousand people in the region died as a result. Also, because of its topicality during the preparation of this paper, the timing of the Solomon Islands earthquake (Mw=8.1) and tsunami of 01 April 2007 is briefly investigated.

Earthquakes of similar magnitude to the 26 December 2004 earthquake are rare, as are tsunamis on the scale which followed. Other examples of ‘large’ earthquakes include the Ennganno earthquake (Mw=7.9) of 2000 (Milsom, 2005), and the Alaskan earthquake (Ms=8.6) of 1964 which led to areas of uplift up to 16 m and subsidence of approximately 2-3 m (Krauskopf, 1972). Such earthquakes are associated with subduction zones, with one tectonic plate of heavier oceanic crust being subducted below one of lighter continental crust (Keller, 1996; Bolt, 2004). The Sumatran-Andaman subduction system between the Indian and SE Asian plates forms the western part of the Sunda Arc, which extends more than 2000 km from Burma to the Sunda Strait. The presence of the Burma microplate between these two major plates means that Sumatran earthquakes cannot be understood merely as the simple interaction of these two major plates. Meltzner *et al.* (2006) suggest that the 26 December earthquake was a result of slip between the Indian plate and Burma microplate below the Andaman and Nicobar islands and Aceh province, Sumatra. The earthquake hypocentre was at a depth of 30 km and the associated fault rupture slipped by 10-20 m. Bilham (2005) suggested the rupture was probably due to an initially rapid slip that slowed as it propagated northwards. This resulted in differential uplift and subsidence of the seafloor and surrounding islands with seafloor uplift of up to 15 m (Teeuw, 2005; Henstock *et al.*, 2006). The detailed pattern of uplift and subsidence associated with this earthquake has also recently been highlighted by Briggs *et al.* (2006) and Subarya *et al.* (2006). The latter indicate that the earthquake caused a rupture up to 1500 km long and 150 km wide along the subduction zone off northern Sumatra, with aftershocks active from the

Andaman Islands to the earthquake epicentre near northern Sumatra.

During the period in which the 26 December 2004 earthquake and its aftershocks occurred, the Radon Research Group at the University of Northampton (UK) was compiling hourly time-series of radon data as part of ongoing investigations into (a) radon anomalies associated with UK earthquakes (Crockett *et al.*, 2006a) and (b) tidal influences on atmospheric radon levels (Crockett *et al.*, 2006b). It was observed that the 26 December 2004 earthquake and its principal aftershocks (approximately 20-30 km depth) occurred in close relation to tidal maxima at new and full moons.

Others have made similar observations. Attempts at rigorous quantification of tidal influences on earthquake incidence can be considered as starting with Schuster in 1897, who developed a measure of probability commonly referred to as ‘Schuster’s test’ (Schuster, 1897; Rydelek *et al.*, 1992; Emter 1997; Wilcock, 2001). Emter’s 1997 review of such research over the previous century observed that (a) relationships are not always significant and (b) assessing the significance of any apparent relationship is not straightforward. Wilcock (2001) in studies of the Juan de Fuca Ridge (a) noted that ocean-floor tidal stresses can be up to an order of magnitude higher than those in continents because of ocean tidal loading and (b) demonstrated that in full and declustered catalogues, the distribution of events appeared to be not by-chance to a high level of confidence. Conversely, Rydelek *et al.* (1992) did not find significant tidal triggering. Tamrazyan (1968) indicated that changes in seismic activity were characterised by cycles that were not well understood, while Kasahara (2002) stated that tides have been implicated in earthquake generation for some time but with limited supporting evidence. More recently, Tanaka (2006) reported tidal triggering in Sumatran earthquakes prior to 26 December 2004.

2. Data Analysis.

The appropriate earthquake catalogues were downloaded from the Advanced National Seismic System database (www.ncedc.org/anss). Ocean tidal-loading cycles for correlation analysis were calculated using the GOTIC2 suite of software (Matsumoto *et al.*, 2001).

2.1. Main Analysis: 26 December 2004 earthquake and its major aftershocks.

The earthquake catalogue for the period around this earthquake shows that the region was relatively inactive until mid-November 2004, then underwent a period of several large earthquakes (each followed by aftershock activity) from 26 December 2004 to 24 July 2005 and has been becoming less active since then. This is revealed by the time-series of daily earthquake frequency as shown in Figure 1, for the period November 2004 – June 2005. This shows clear episodes of high earthquake activity, each associated with a major earthquake triggering aftershocks (as described below). The ten-lunar-month period between the full moons of 28 October 2004 and 19 August 2005 was chosen for detailed investigation as it brackets this active period.

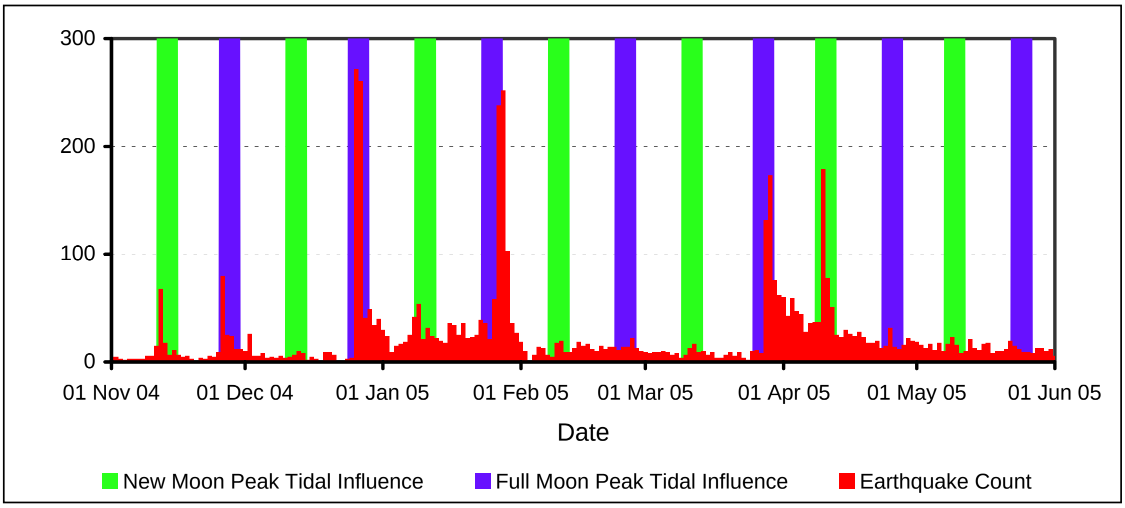

FIGURE 1. Earthquake activity and tidal maxima.

Spatial cluster analysis reveals that the earthquake activity occurred in two distinct geographical groups, with the boundary between the two lying in mid-Java. Of interest here is the main western group of 4943 earthquakes (Mb=3.5 and greater) centred on northern Sumatra. There is also an eastern group of 864 earthquakes (Mb=3.5 and greater) centred close to East Timor. The activity prior to 26 December 2004 occurred mainly in two episodes within the eastern group associated with: (a) the Mw=7.5 earthquake of 11 November 2004 (new moon, 12 November) and (b) the Mw=7.1 earthquake of 26 November 2004 (full moon). The remainder of the activity occurred mainly in four major episodes in the western group associated with: (a) the great earthquake of 26 December 2004 (full moon) and the associated major earthquakes of (b) 24 January 2005 (Mw=6.3, full moon 25 January), (c) 28 March 2005 (Mw=8.7, full moon 25 March) and (d) 10 April 2005 (Mw=6.7, new moon 08 April). Such episodes comprise relatively large key earthquakes followed by clusters of smaller triggered aftershocks, and are clearly visible in Figure 1.

The timing of the key major earthquakes is shown in Figure 2, which again shows a clear relationship to the tidal maxima. These are revealed by declustering (Musson, 1999). Owing to the large magnitudes of these earthquakes, no spatial constraints were applied within the geographical groups. Also, in order to remove as much aftershock 'noise' as possible, the longest safe look-ahead widow, 9 days, was used (resulting from the combination of the duration of the aftershock-decay, the timing of these earthquakes in relation to the tidal maxima and the 14-15-day period between consecutive tidal maxima).

The basic tidal periodicity of earthquake incidence apparent in Figures 1 & 2 can be confirmed by Fourier or maximum entropy spectral analysis of the full and declustered earthquake catalogues. Within the resolution of the spectra obtained, and despite degradation due to the 'jitter' of earthquake incidence around the tidal maxima, the resulting spectra show clear components corresponding to the tidal-strength (14-15 days) and lunar (29-30 days) periods.

Since any tidal influence must originate from the tidal forces, any tidal periodicity of the earthquakes can be revealed by cross-correlation of the earthquake time-series with the modelled variation in tidal force – tidal-loading in this case (the earthquake-incidence peaks are centred on the tidal-loading maxima, not the earth-tide maxima). The cross-correlations are shown in Figure 3, for both the full and declustered western-group catalogues. Note that the magnitude of the correlation coefficient is small owing to the dissimilarity of shape of the of the shapes/waveforms of the tidal-loading and earthquake time series. This is discussed in more detail in previous papers which examined tidal cycles/periods in radon emissions (Crockett *et al.*, 2006b) and these Sumatran earthquakes (Crockett *et al.*, 2006c & 2007). Significantly, however, both cross-correlation curves show cyclic variation with period 14-15 days (the tidal-strength period), confirming the presence of tidal cycles in earthquake incidence. For the full catalogue, the earthquake-incidence peaks follow the tidal-loading maxima by 0-1 days (positive lag indicates peak earthquake activity lagging behind tidal-loading maxima); for the declustered catalogue, the peaks precede the tidal loading maxima by a similar period, *i.e.* these peaks occur between the peak earth-tides (at new and full moons) and the associated tidal loading maxima which occur 2-3 days later.

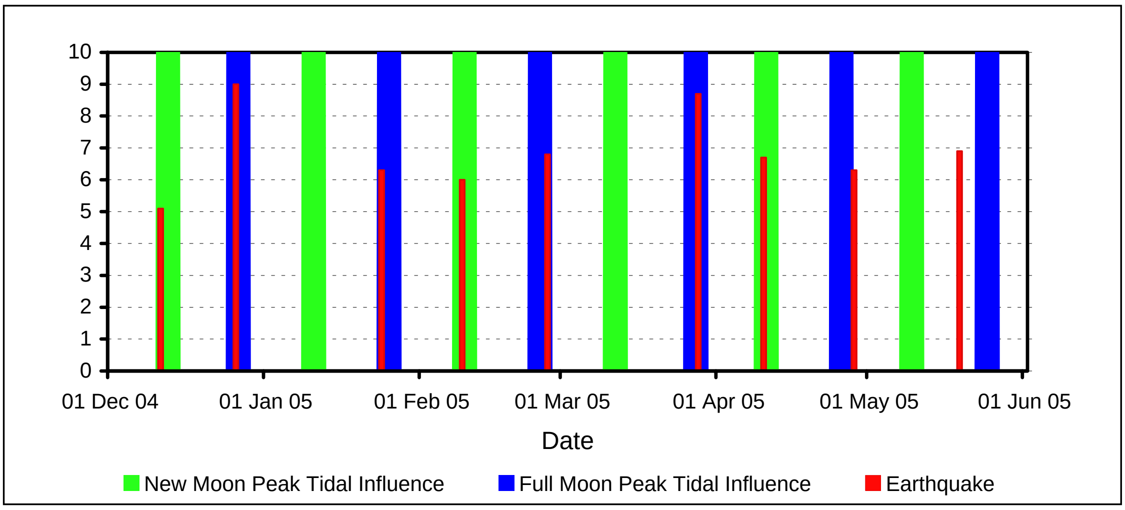

FIGURE 2. Timing of key major earthquakes, western group, and tidal maxima.

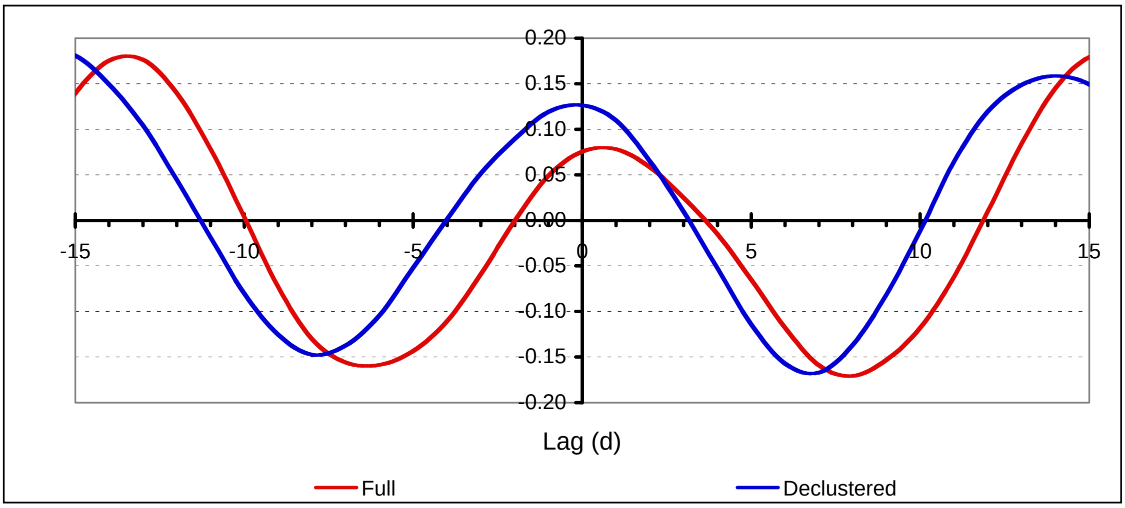

FIGURE 3. Cross-correlation of earthquake activity with tidal-loading.

In an attempt to better quantify the correlation of these dissimilar but essentially synchronous waveforms, a novel method is under development at the University of Northampton – 'window correlation' (Crockett *et al.*, 2006b&c & 2007). In essence, this entails windowing the earthquake catalogue according to quarter lunar-cycles centred on the tidal-loading maxima (*i.e.* new and full moons) and tidal-loading minima (*i.e.* first and third quarters), noting that the maxima and minima typically lag the lunar phases by 2-3 days. The earthquake-incidence totals are then calculated for the four cumulative quarter-cycles which, taking account of earthquake incidence peaks at new and full moons, can be combined to produce cumulative totals for the tidal maxima, $n_{\max}$, and tidal minima, $n_{\min}$,:

$$n_{\max} = n_N + n_F \text{ and } n_{\min} = n_N + n_F \quad (2.1)$$

where n_N and n_F are the cumulative tidal maxima quarter-cycle totals (new and full moons respectively), and n_{Q1} and n_{Q3} are the cumulative tidal minima quarter-cycle totals, (first and third quarters respectively). Clearly, this can be modified to take account of earthquake-incidence (or other) peaks associated with other quarter-cycles.

The quarter-cycle windows are then offset (lagged) for these tidal references over a range of intervals and the calculations repeated to produce sequences of cumulative totals. If the catalogue does not contain any tidal-periodic behaviour then, for all offsets/lags:

$$n_N \approx n_F \approx n_{Q1} \approx n_{Q3} \text{ and } n_{\max} \approx n_{\min} \quad (2.2)$$

However, if the catalogue contains tidal-periodic behaviour, for an offset/lag corresponding to that revealed by cross-correlation, the difference

$$n_{\max} - n_{\min} \quad (2.3)$$

will maximise.

This can be conveniently represented via the normalised ratio:

$$r = \frac{n_{\max}}{n_{\max} + n_{\min}} = \frac{n_N + n_F}{n_N + n_F + n_{Q1} + n_{Q3}} \quad (2.4)$$

which allows direct comparison between, for example, full and declustered catalogues.

The variation of this ratio shown in Figure 4. It clearly reveals the same underlying cyclic variation with the same lag as the cross-correlation coefficients for each earthquake catalogue. In essence, the ratio is different measure of correlation in time, one which is independent of the shapes/waveforms of the time-series.

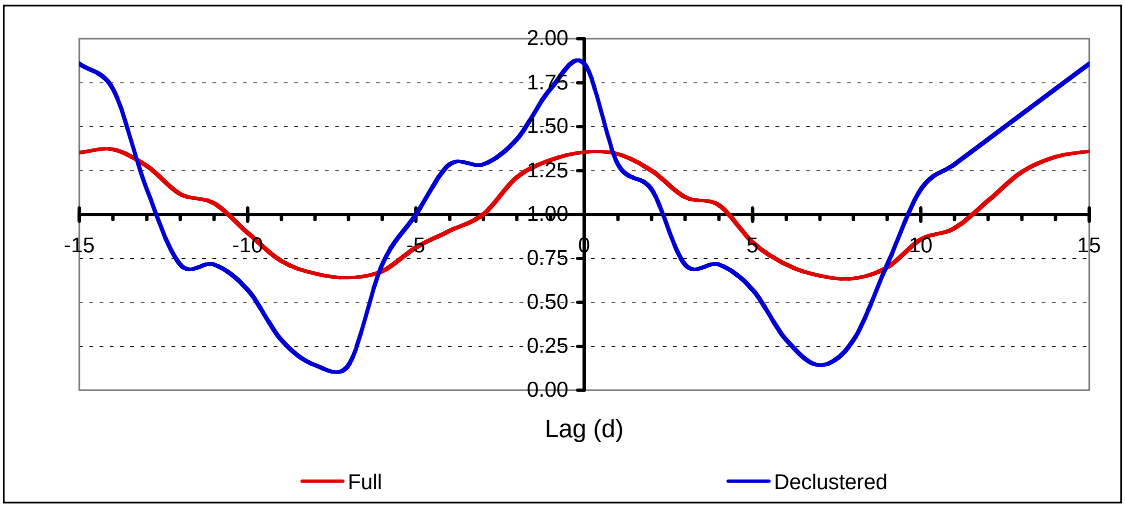

FIGURE 4. Window correlation – variation of the new-full ratio.

2.2. Other Indonesian earthquakes and tsunamis: 1992 and 1994.

Of the three other Indonesian earthquake/tsunami events considered, only that of 12 December 2002 displayed any tidal synchronicity, as shown in Figure 5. Also, it is clear that whilst the event of 12 December occurred close to a full moon, the remainder of the activity around that time does not reveal any significant tidal synchronicity, with peaks in activity occurring at various phases of the tidal-strength cycle.

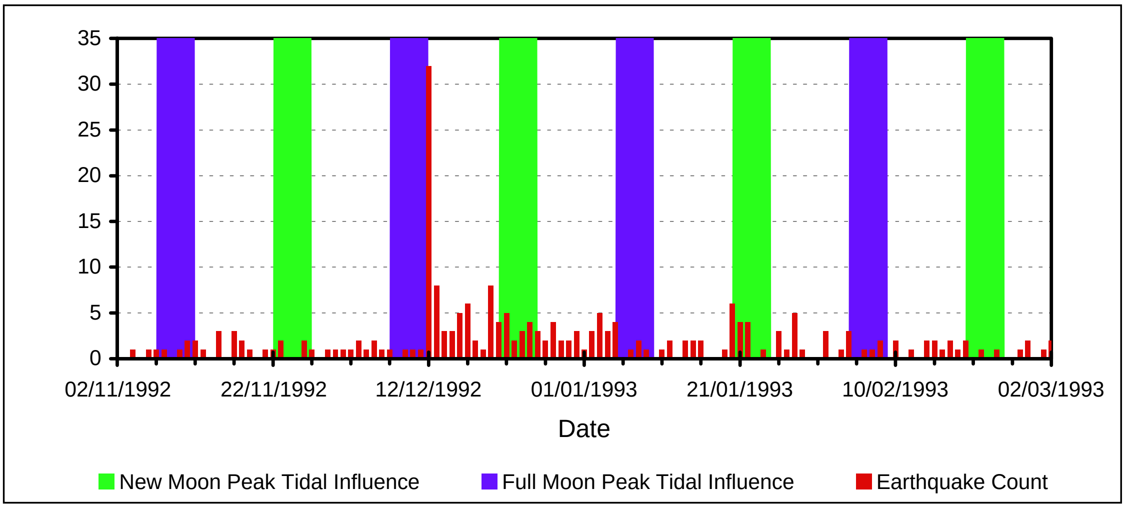

FIGURE 5. Earthquake activity and tidal maxima, Indonesia 1992-1993.

2.3. Solomon Islands earthquake and tsunami: 2007 (preliminary).

The Solomon Islands earthquake/tsunami event of 01 April 2007 occurred close to a full moon and was preceded by two tidally-synchronous episodes on 17 February 2007 (new moon) and 31 January (full moon), although these were smaller.

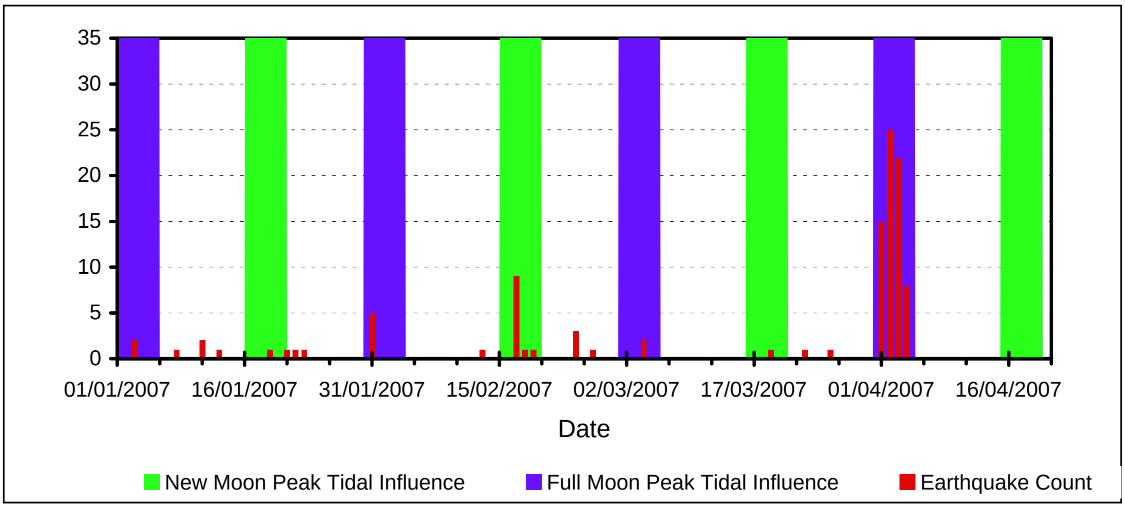

FIGURE 6. Earthquake activity and tidal maxima, Solomon Islands 2007.

3. Statistical significance.

The earthquake catalogues presented in Figures 1, 5 and 6, and their declustered counterparts, all indicate some correlation between periodic behaviour apparent in the earthquake data and tidal-strength cycles, correlation which has been further demonstrated as described and shown in Figures 3 and 4. However, there is a probability that the timings in the earthquake data occur by chance and are not cyclic with the tidal-strength (spring-tide) period of 14-15-days or the lunar month of 29-30-days.

The probabilities that these tidal-cyclic variations have arisen by chance can be evaluated using χ^2 statistics on the cumulative quarter-cycle totals evaluated accounting for the lag. Another measure of probability can be obtained using 'Schuster's test' (Schuster, 1897; Rydelek *et al.*, 1992; Emter 1997; Wilcock, 2001), noting that this must be applied on the tidal-strength cycle and not the lunar month so as to avoid problems associated with sub-cyclic symmetry and false negatives. These data are presented in Table 1.

Earthquake Catalogue	χ^2	Schuster
Indonesia 2004, full	8.01E-131	4.29E-191
Indonesia 2004, declustered	0.001	0.012
Indonesia 1992, full	0.024	0.367
Indonesia 1992, declustered	0.257	0.791
Solomon Islands 2007, full	5.45E-16	2.57E-22
Solomon Islands 2007, declustered	0.005	0.017

TABLE 1. Probabilities of occurrence by chance.

The full-catalogue figures represent a 'headline' case: these figures include the aftershock activity and so are not a true representation of the probability of cyclic behaviour of the key major earthquakes, which is better represented by the declustered-catalogue figures. For the Indonesia-2004 and Solomon Islands catalogues, both the χ^2 and Schuster's tests show that the probabilities of occurrence by chance are small (negligibly so for the full catalogues) indicating that the probabilities of tidal dependence are correspondingly high. This is not the case for the Indonesia-1992 catalogues, indicating significantly lower probabilities of tidal dependence, confirming the observation made regarding Figure 5.

4. Possible Mechanism for the 26 December 2004 event.

Tidal-force has two basic influences on the stresses in the Earth's crust. These are (a) 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) and (b) the tidal movement of water which cyclically loads and unloads regions of the Earth's crust, *i.e.* (ocean) tidal loading (e.g. Baker, 1984; Farrell, 1972). 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 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. 29-30-day tidal-cycle (i.e. lunar month). 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 tidal-loading cycles.

The subduction zone of interest here is subject to asymmetric tidal loading because the tectonic plate on one side is covered by the Indian Ocean whereas the other side comprises landmasses, including the Indonesian islands, and shallower seas. Consequently the descending Indian plate may be subject to greater tidal loading than the Asian plate. Our analysis showed strong agreement between the earthquake-incidence peaks and tidal-loading maxima (as against the earth-tide maxima), suggesting that tidal-loading rather than earth-tides is the dominant factor, and so we hypothesise that this asymmetric loading causes the crust to flex in a hinge-like manner at the complex plate boundary. The observed relationships suggest that the cyclical crustal flexing, which will be at a maximum for the 2-3-day periods around the earth-tide and tidal-loading maxima, 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'.

5. Conclusion.

Correlation between the incidence of Indonesian earthquakes in the period around 26 December 2004 and lunar/tidal phases has been observed and quantified and found to be significant. On average, for the ten-month period analysed, the earthquake-incidence maximum for major earthquakes was 86% greater than average and preceded the tidal-loading maximum by 0-1 days, occurring between the earth-tide and tidal-loading maxima associated with the new or full moon.

Similarly, correlation between he incidence of Solomon Islands earthquakes in the period preceding 01 April 2007 and lunar/tidal phases has been observed and quantified and found to be significant. On average, for the six-month period analysed, the earthquake-incidence maximum for major earthquakes was 50% greater than average and preceded the earth-tide maximum (new or full moon) by 2-3 days.

The correlation is less significant for the Indonesian earthquake/tsunami event of 12 December 1992 and, for the Indonesian earthquake/tsunami events of June 1994 and October 1994, no lunar/tidal correlation was apparent.

In both the cases where the correlation is significant, the association of variations in earthquake incidence with tidal-loading cycles appears intuitively reasonable but the specific mechanisms await investigation at the present time. Also, this significant tidally synchronous behaviour preceded the earthquake/tsunami event itself, indicating that under some circumstances at least, monitoring seismic activity might yield an early warning of an earthquake/tsunami event.

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