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Earthquake-Tide Correlation

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Summary

The detection of moonquakes that occur when the Moon is at perigee has prompted a search for tidal effects on earthquake occurrences. An attempt was made to correlate earthquakes listed in the CGS-NOA epicentre determinations with the tidal phase of semidiurnal tides. This study was confined to several seismic regions representative of tectonic and non-tectonic regions. An extended form of Schuster's test was used to decide whether significant correlations existed. Though some tidal influences could be accepted at a 5 per cent significance level, the effect was not consistent or stable with time. Earthquakes, if they are affected by tides, show a slight tendency to occur at times when the tidal stress is changing most rapidly. Insufficient data was available to compare tectonic to non-tectonic areas.

An analysis of the Japanese aftershock sequence which began 1969 August 11 was found to have no significant tidal correlation.

Introduction

It is still controversial whether or not solid Earth tides trigger earthquakes. Many statistical studies of earthquake catalogues have been performed to find periodicities or correlations with extraterrestrial forces. Knopoff (1964) concluded from his study of the earthquakes detected by the Pasadena network from 1934 to 1957 that no correlation existed between earthquakes and tides. On the other hand Ryall, Van Wormer & Jones (1968) found that aftershocks of the Truckee Earthquake September 1966 sequence had a strong, 25-hr periodic component with more earthquakes occurring at minimum tide. Recent results from the Apollo missions showed that moonquakes coming from a certain region of the Moon occur only at tidal maximum when the Moon is at perigee to the Earth.

Tidal forces introduce stresses of the order of 5 mbar. Though these stresses are small in comparison to tectonic stresses on Earth they are quasi-periodic, rapidly varying and possibly a triggering agent of earthquakes.

In an earlier paper (Shlien & Toksöz 1970), it was concluded that no periodicities between 2 and 256 days were present either locally or world-wide in the U.S. Coast and Geodetic Survey Epicenter determinations. This does not rule out the possibility of correlating earthquakes with semidiurnal tides. To test this hypothesis an analysis identical to Knopoff (1964) was performed on the CGS-NOA epicentre determinations and a cross-covariance analysis was made of the 1969 August 11 Japanese aftershock sequence with the equilibrium ocean tides. The next two sections describe these analyses.

Tidal phase analysis

Since it is not known whether earthquakes have a tendency to occur at maximum tide or minimum tide or at any time in between, a tidal-phase approach was taken. To find out whether such a tendency, if it exists, is consistent all over the world, the analysis was applied to several distinct seismic regions. The seismic regions were selected so as (1) to be generally close to the equator where tidal effects are largest, (2) to be representative of both tectonic and non-tectonic regions, and (3) to have a reasonable number of events such that meaningful statistics could be obtained. The boundaries of the regions are listed in Table 1.

If enough events were reported in a particular region then the analysis was broken up into several disjointed time intervals so that time variations could be detected.

The basic approach used here is identical to Knopoff's (1964) real-time analysis. For every earthquake the equilibrium ocean tide was calculated for 12-hr intervals before and after the origin according to Munk & Cartwright (1965). The minimum- and maximum-tide times contiguous to every earthquake were estimated by interpolation. In general the time between minimum and maximum tide was found to fluctuate between 4 and 8 hr. For this reason tidal-phase rather than real-time was used. The time between the minimum and the maximum was divided into 50 units, where tidal maximum was 50 units. If the earthquake occurred before the maximum its tidal phase was between zero and 50, otherwise its tidal phase was between 50 and 100.

Table 1

South-western USA	15° N–45° N	105° W–120° W
Japan	20° N–40° N	135° E–145°E
Tonga	15° S–35° S	172° E–178° W
Greece and Turkey	35° N–40° N	20° E–30° E
Sandwich Islands	55° S–65° S	22° W– 30° W
Afghanistan and Tadshik	35° N–40° N	65° E– 75° E

Histograms of the tidal phase for the various regions and time intervals are shown in Fig. 1. The distribution should be uniform if earthquakes occurred completely independently of the tides. Though there appears to be considerable fluctuation from the uniform distribution, it is difficult to conclude visually whether these are random effects or are actually indications of earthquakes tending to more likely occur at certain tidal phases than at others. To test these hypotheses an extended form of Schuster's (1897) test was applied to the tidal phase of earthquakes. In principle, the test estimates the first two Fourier components of the tidal phase distribution and determines whether these components are significantly large. Statistics R_1, R_2, ϕ_1, ϕ_2 were computed using

$$A_1 = \sum_{i=1}^{n} \cos\left(\frac{2\pi}{100} T_i\right) \qquad A_2 = \sum_{i=1}^{n} \cos\left(\frac{2\pi}{50} T_i\right)$$

$$B_1 = \sum_{i=1}^{n} \sin\left(\frac{2\pi}{100} T_i\right) \qquad B_2 = \sum_{i=1}^{n} \sin\left(\frac{2\pi}{50} T_i\right)$$

$$R_1^2 = A_1 + B_1^2 \qquad R_2^2 = A_2^2 + B_2^2$$

$$\phi_1 = \frac{100}{2\pi} \tan^{-1}(B_1/A_1) \qquad \phi_2 = \frac{100}{2\pi} \tan^{-1}(B_2/A_2)$$

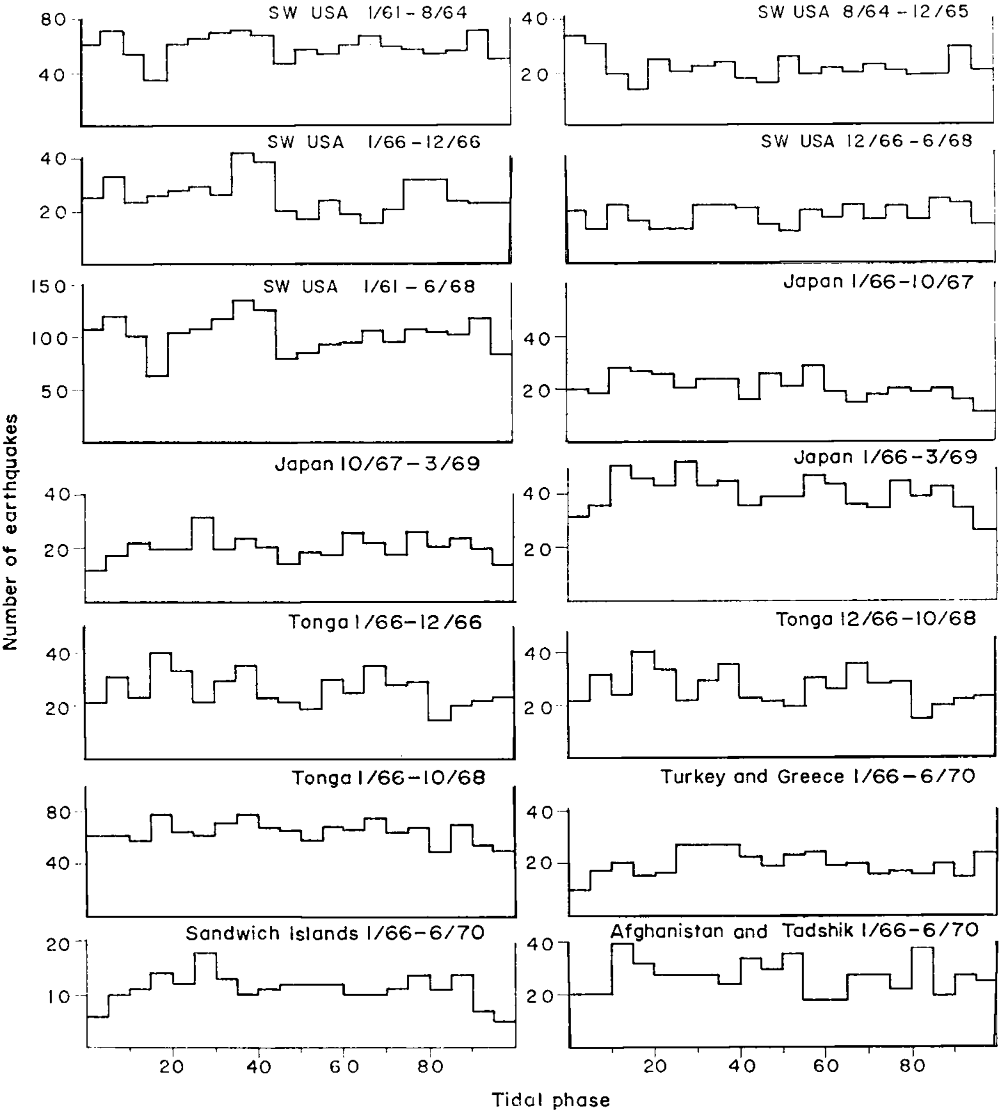

FIG. 1. Histograms of number of earthquakes versus tidal phase for different regions and time periods.

where T_i is the tidal phase of the ith earthquake and n is the total number of earthquakes analysed. This can be visualized as follows. Each earthquake is represented by a unit vector whose direction is determined by its tidal phase. Thus for the first Fourier component, all events occurring at tidal phase 0 or 100 corresponding to a minimum tide would be represented by vectors pointing north while earthquakes occurring at maximum tide would be represented by vectors pointing in the opposite direction. The vectorial sum of this set will point towards the tidal phase that earthquakes tend to occur, and its magnitude is indicative of the strength of the tendency. Now if earthquakes occur completely randomly and independently of the tides, then A_1, A_2, B_1, B_2 are normally distributed with zero mean and variance $n/2$. Therefore both ${R_1}^2$ and ${R_2}^2$ are χ^2 distributed with two degrees of freedom. The probability P that R_1 or R_2 is larger than some value R is just

$$P = \exp(-R^2/n).$$

The second Fourier component R_2, is used to detect the tendency of earthquakes occurring at two opposite phases. If earthquakes have an equal tendency to occur at both minimum and maximum tide, Schuster's test as was originally devised would not detect this tendency.

The results of the test applications of Schuster's are listed in Table 2. P_1 and P_2 are the probabilities of observing an R larger than R_1 and R_2, respectively, assuming that earthquakes occur independently of tides. Thus if either P_1 or P_2 is very low, it implies that it is not likely that earthquakes are occurring completely randomly.

Table 2

Earthquake-tide correlation

Data	R_1	θ_1	P_1	R_2	θ_2	P_2	n
SW USA							
1/61–8/64	34	41	0·18	31	69	0·24	700
8/64–12/65	27	1	0·20	18	99	0·47	450
1/66–12/66	35	17	0·11	46	70	0·02	575
12/66–6/68	16	83	0·47	13	83	0·60	350
1/61–6/68	43	16	0·39	86	75	0·03	2075
Japan							
1/66–10/67	32	32	0·09	15	25	0·56	425
10/67–3/69	2	34	0·98	32	55	0·08	400
1/66–3/69	34	32	0·24	31	47	0·31	825
Tonga							
1/66–12/66	22	28	0·38	45	37	0·02	525
12/66–10/68	9	82	0·89	18	68	0·64	750
1/66–10/68	14	25	0·86	43	44	0·23	1275
Turkey and Greece							
1/66–6/70	32	43	0·07	24	79	0·22	400
Sandwich Islands							
1/66–6/70	14	41	0·42	20	55	0·16	225
Afghanistan and Tadshik							
1/66–6/70	10	23	0·68	6	35	0·87	275
All	117	95	0·08	135	61	0·03	5075
Synthetic	27	66	0·22	15	95	0·62	500

For most of the applied tests, deviations from the uniform distribution were insignificant. The lowest P found was P_2 for South-western U.S.A. during the year 1966. At a 5 per cent significance level one could conclude that there are tidal influences for that region and time. (Significance level is the probability that one rejects the null hypothesis, earthquakes are independent of tides, when it is actually true.) In general, more significant deviations were observed in the second Fourier component than the first Fourier component, i.e. there seem to be two peaks in the tidal phase distribution of earthquakes. The peaks when they occur, are before either maximum or minimum tide, implying that the triggering effect is more likely the rate of change in stress which would be maximum at tidal phases 25 and 75.

The sensitivity of these tests depends on the sample size n. The more earthquakes available, the easier it is to detect a weak tidal effect. If tidal influences on earthquakes is constant and greater than zero, then P_1 and P_2 should decrease with n. But on the contrary, it was found that P_1 and P_2 had the opposite tendency. Very curiously the largest tidal effects were only found in the year 1966. Thus it can be concluded that if a tidal effect exists it is not constant with time.

The tendency for earthquakes to occur less randomly in the year 1966 is hard to explain. Tidal forces did not appear to be stronger that year. In the case of the South-western U.S.A., there were two small aftershock sequences that contributed about 100 events. No tendency was found for the earthquakes occurring around the peaks at tidal phase 40 and 80 to be restricted to any time, area or aftershock sequence. To check that there were no systematic errors in the analysis, a synthetic earthquake catalogue was generated using random numbers for the year 1966 in South-western U.S.A. As expected the catalogue showed no correlation with tides.

It is not possible to conclude from this analysis that tidal effects are any larger or smaller in tectonic regions than in non-tectonic regions. Fewer earthquakes occur in non-tectonic regions so that it is harder to detect a tidal correlation.

In conclusion, this analysis had shown that the role of tidal forces on earthquake occurrences is minimal. Because the tidal effect on earthquakes is not even consistent with time, catalogues covering a larger time span would probably not help in definitely ascertaining whether the tidal effect is there.

Japan earthquake sequence 1969 August 11 (Shikotan)

In a large aftershock sequence, the crust is in a highly unstable state. Many events occur in a short period of time comparable to tidal variations. Therefore, an aftershock sequence is very suitable for a tidal correlation study.

This aftershock sequence was well recorded by LASA's detection log. A beam, formed by phasing the array, covered the aftershock area and detected most events down to magnitude 3·5. Since the detection process was done completely automatically, having a fixed detection threshold, and involving no human interpretation, it is believed that it is a highly reliable source for a statistical study.

Over 1000 events occurred in this aftershock sequence. By counting the number of events in hourly intervals from 1969 August 11 to September 4, a time series was formed. This was cross-correlated with the equilibrium ocean tide computed on an hourly basis. The two time series for the first 15 days of the sequence are plotted side by side in Fig. 2.

The trend was removed from the aftershock time series by a piecewise linear function continuous over 29 hr. The autocovarience and cross-covariance were computed using the following equations

$$C_{nn}(k) = \frac{1}{n-k} \sum_{i=1}^{n-k} n(i)\, n(i+k)$$

$$C_{nt}(k) = \frac{1}{n-k} \sum_{i=1}^{n-k} t(i)\, n(i+k)$$

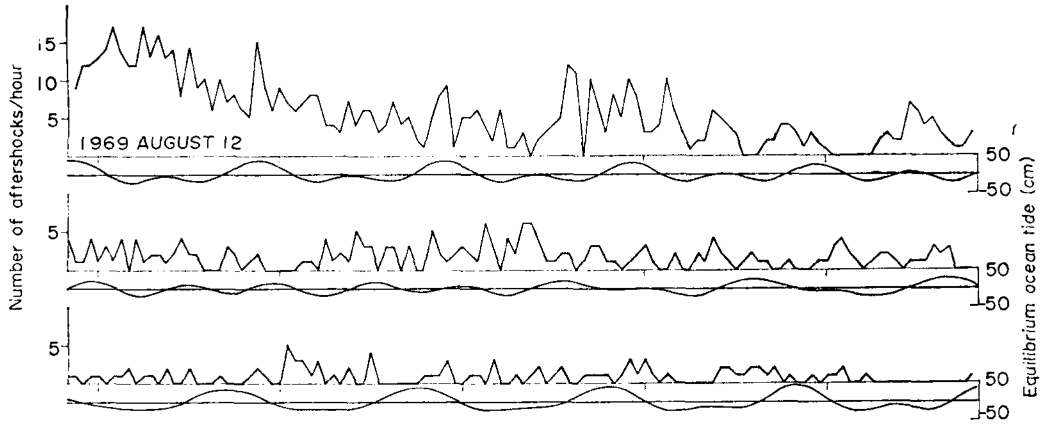

FIG. 2. Time series of number of aftershocks per hour intervals and computed equilibrium ocean tide height in centimetres. Tick marks occur every 25 hr.

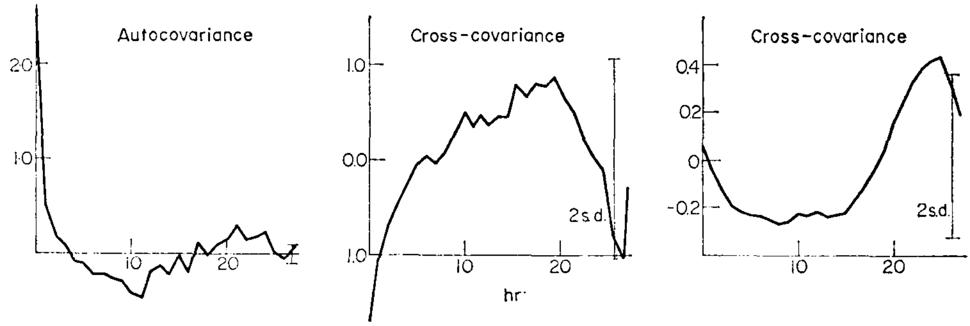

FIG. 3. *Left:* Autocovariance of the detrended aftershock time series in number of earthquakes versus hour lags. *Middle:* cross-covariance of the detrended aftershock time series with tidal height (centimetres) versus hour lags. *Right:* cross-covariance of the detrended aftershock line series with hourly change in tidal height (centimetres) versus hour lags.

where $n(i)$ is the number of earthquakes in ith hours after the trend was removed, $t(i)$ is the tide height with mean removed at ith hour, and where $i = 1, \dots N$. Fig. 3 shows the autocovariance function of this aftershock time series and its cross-covariance with both the height of the equilibrium ocean tide in centimeters and the hourly change of height.

The variance of the autocovariance and cross-covariance functions are given by

$$\operatorname{var}\left(C_{nn}(k)\right) = \frac{C_{nn}(0)}{N-k}$$

$$\operatorname{var}\left(C_{nt}(k)\right) = \frac{\left(C_{nn}(0)\, C_{tt}(0)\right)^{\frac{1}{2}}}{N-k}$$

provided that $n(i)$ is a white noise process and is uncorrelated with $t(i)$ (Box & Jenkins 1970). $C_{tt}(0)$, the variance of the tidal height (change of height) time series was computed to be 260·(33·) cm^2. The error bars in Fig. 3 indicate 2 standard deviations.

The autocovariance function of the aftershock sequence in Fig. 3 suggests that there is a 22-hr periodicity. The periodicity is apparent in Fig. 2 only for the first 4 days of the aftershock sequence.

In estimating these covariance functions there was a certain subjectiveness in removing the trend. The purpose of the trend removal was to eliminate the contributions to the covariance functions introduced by the fact that aftershock activity decays according to a fixed pattern. Because this aftershock sequence appears to consist of at least two bursts of activity it was decided to use a piecewise linear function rather than try to fit the whole sequence to an exponential or power law.

The two cross-covariance functions do not confirm the existence of any tidal influence. The variations of the two functions are almost contained by the two standard deviation error bars. More than 50 per cent of the aftershocks detected occurred in the first four days of the series. Thus the covariance functions are very largely influenced by these four days. The negative peak for the zero lag of the middle graph of Fig. 3 is due partly to the lower activity during the first 5 hr of the sequence. Since the 22-hr periodicity is entirely due to the first 4 days of the sequence it is very questionable whether it is something significant. Thus it would be concluded from the study of this aftershock sequence that if there is a tidal effect it is hidden by the random fluctuations of the aftershock activity.

Conclusions

This study did not prove the existence of tidal correlation with earthquakes. While a tidal phase analysis of the CGS-NOA catalogue had detected a possible tidal effect for the year 1966 in South-western U.S.A. and the Tonga regions, this effect did not persist over any other time periods. Applying an extended form of Schuster's test, there appeared to be a small tendency for earthquakes to occur before minimum and maximum tides in these two regions. No significant cross-covariance could be detected for the 1969 August 11 Japan aftershock sequence.

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