'Clean' spectral analysis of long-term sea-level changes

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ABSTRACT

A new 'clean' spectral technique has been applied, for the first time, to analyse a record of long-term sea-level fluctuation during the last 200 million year (Myr). The technique is based on a one dimensional complex deconvolution algorithm and removes the effects of the data sampling as well as the artifacts arising from the choice of data window. The analysis reveals a dominant periodicity of 33 Myr in the sea-level variations. This periodicity compares well with the known half-period of the Sun's oscillation perpendicular to the galactic plane. Interestingly, a 33 Myr periodicity can also be correlated with the reported mass extinction cycles and other geological periodicities. The results suggest galactic forcing as a possible driving mechanism for quasi-periodic terrestrial processes.

Terra Nova, **2**, 138–141

INTRODUCTION

Global sea levels have undergone major changes during the geological past. These changes have occurred on time scales ranging from a few million years to a few months and result from a vast set of physical forces, of endogenetic and/or exogenetic origin. The possible internal sources include tectono-eustacy, orogeny, sea-floor spreading, glacio-eustacy, etc. However, Earth is recognized as an open system in its galactic environment and has extra-terrestrial interactions. These interactions, occurring on a time-scale of hundreds of millions of years, may be deciphered clearly in long term earth processes.

Modern time series analyses have played an important role in the search for such deterministic patterns in geological phenomena and to understand the causative physical mechanisms operating over different time scales. Recent Mega-cycle-analyses of geological phenomena, including major tectonic episodes, intrusions (kimberlites and carbonatites), biological mass extinctions, and terrestrial impact cratering have claimed the dominance of 260(±25), and 33(±3) Myr periodicities (Rampino and Stothers, 1984). A possible correlation between periodicities in the geomagnetic reversals and galactic motions of the solar system had also been reported by Negi and Tiwari (1983), who found in their analysis of geomagnetic reversals during the last 570 million years, statistically significant (99%) periodicities of 33(±1) and 285 Myr. In the present investigation we analyse the updated sea-level data of Haq *et al.* (1987) using a recently developed 'clean spectral algorithm' developed by Robert *et al.* (1987).

Clean spectral algroithm

Robert *et al.* (1987) have presented an efficient ('clean') spectral technique especially for unequally spaced data in a time series analysis. Application of this technique has also been reported by others (Drehar *et al.*, 1986; Duvall and Harvey, 1984) for analysing astronomical data. The 'clean' algorithm removes the artefacts introduced by missing data. The method is based on a complex one-dimensional version of the clean deconvolution algorithm widely used in two-dimensional image reconstruction. Some essential features of the algorithm are presented below.

According to convolution theorem the Fourier transform of the sampled signal is the convolution of the spectrum with the sampling function, i.e.

$$D(\nu) = F(\nu)^{*}W(\nu) = \int_{-\infty}^{\infty} d\nu' F(\nu')W(\nu-\nu') \qquad (1)$$

where $D(\nu)$ and $W(\nu)$ are the dirty spectrum and spectral window function, respectively.

The $D(\nu)$ and $W(\nu)$ can be calculated directly from the discrete data and are given by:

$$D(\nu) = \frac{1}{N}\sum_{r=1}^{N} f(\nu)e^{-2\pi i\nu t_r} \qquad (2)$$

and

$$W(\nu) = \frac{1}{N}\sum_{r=1}^{N} e^{-2\pi i\nu t_r} \qquad (3)$$

To apply 'clean' to the deconvolution of equation (1), as an example, we consider a single harmonic component (cosinusoid) with harmonic amplitude A, frequency ν' and phase constant ϕ'. The spectrum of this signal is $F(\nu) = a\delta(\nu-\nu')+a^{*}\delta(\nu+\nu')$ where $a = \frac{A}{2}e^{-i\phi}$ and the time function is given by:

$f(t) = A\cos(2\pi\nu' t+\phi')$.

ITERATIVE PROCEDURE FOR CLEAN ALGORITHM

(1) Beginning with the dirty spectrum $D(\nu)$, we find first the amplitude and frequency of the spectral peak component using the equation

$$C^{i} = ga(R^{i-1}; \nu^{i}) \qquad (4)$$

where

$$a(D; \nu) = \frac{D(\nu)-D^{*}(\nu)W(2\nu)}{1-|W(2\nu)|^{2}} \qquad (5)$$

(2) Remove the contribution of this

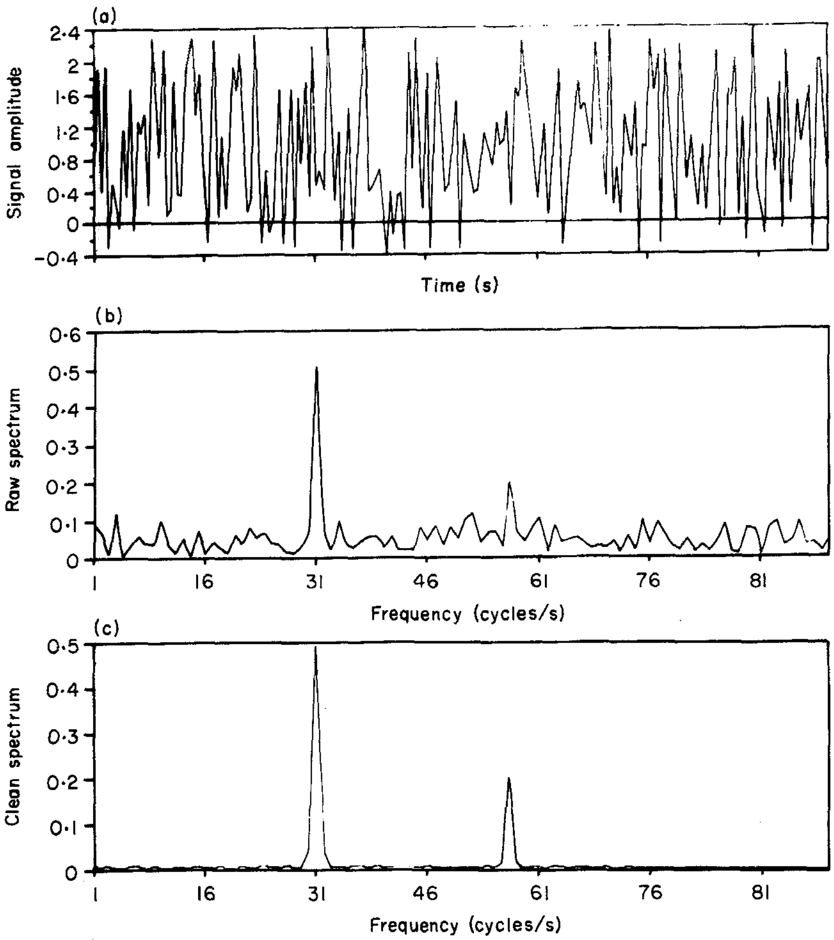

Fig. 1. (a) *Synthetic test data of 201 randomly spaced data points with known cycles of 31 and 57 units.* (b) *Raw Fourier amplitude spectrum of the test data.* (c) *Fourier spectrum using clean algorithm.*

component, including its side lobes, by subtracting the response of the signal as in equation (4) from $D(\nu)$. This will form the first residual spectrum R'. To prevent errors from destabilizing the clean procedure preferably a fraction g of the spectral component is subtracted.

(3) This iterative procedure is repeated to obtain successive approximations, i.e. R', R'', . . . R^N. After completion of the N^{th} step we have a set of N spectral clean components and residual spectrum R^N. In general, the iterative process for the i^{th} residual component is given by:

$$R^i(\nu) = R^{i-1}(\nu) - [C^iW(\nu-\nu^i)+C^{i*}W(\nu+\nu^i)] \quad (6)$$

with $R^0 = D(\nu)$

(4) After determining all the spectral clean components, they are convolved with the clean beam $B(\nu)$. $B(\nu)$, which has a Gaussian shape of amplitude with $B(0) = 1$ and linear slope in phase, is chosen to fit the central peak of $W(\nu)$.

(5) Finally the clean spectrum $S(\nu)$ is given by:

$$S(\nu) = \sum_{i=1}^{K}[C^iB(\nu-\nu^i)+C^{i*}W(\nu+\nu^i)] + R^K(\nu) \quad (7)$$

SEA-LEVEL RECORD AND CLEAN SPECTRAL ANALYSIS

A detailed and precise sea-level record for the last 200 Myr by (Haq *et al.*, 1987) is now available. It was used for the present purpose since it is based on a time scale, obtained from multiple dating techniques such as magnetostratigraphy, chronostratigraphy and biostratigraphy. However, there is some controversy regarding the tiny 'wiggles' present in the data (Gradstein *et al.*, 1988). Mathew (1988) and Haq *et al.* (1988) have maintained that these smaller boundary sequences are accurately resolved and the sea-level record published by them is, perhaps, the best record as yet available for analysing long-term harmonic components.

The salient features of the 'clean' technique are demonstrated, first by applying it to synthetic test data. A 201 sample, randomly spaced, data set with known frequencies of 31 and 57 cycles is used for this purpose. This data, its raw Fourier spectrum and corresponding clean spectrum are displayed in Fig. 1(a,b,c).

A comparison of raw spectrum (Fig. 1b) of the test data with its clean version (Fig. 1c) clearly brings out the resolving power of the 'clean' spectral algorithm.

This same technique has been applied to the above mentioned sea-level fluctuation record. Here, the data values are sampled at uneven intervals by selecting 'highs' and 'lows' from the original record. In order to minimize the effect of seasonal terms in the data we have removed the seasonal trend by fitting a 5^{th} order polynomial curve to the original data. The original sea-level record and the detrended curve are shown in Figure 2(a,b).

We have then applied 'clean' algorithm to the detrended data. The results of this analysis are presented in Fig. 3(a,b.)

The raw spectrum (Fig. 3a) of the sea-level variation record exhibits a noisy spectrum with power oscillations at a number of frequencies including high amplitudes for 33, 16 and 10 Myr terms. The corresponding clean spectrum (Fig. 3b) reveals a dominant spectral peak at 33 Myr. Like the maximum entropy method, clean spectral analysis does not require a formal statistical significance test to be performed for testing the reliability of the spectral peaks. The clean spectral estimators are based on uneven sampling and the

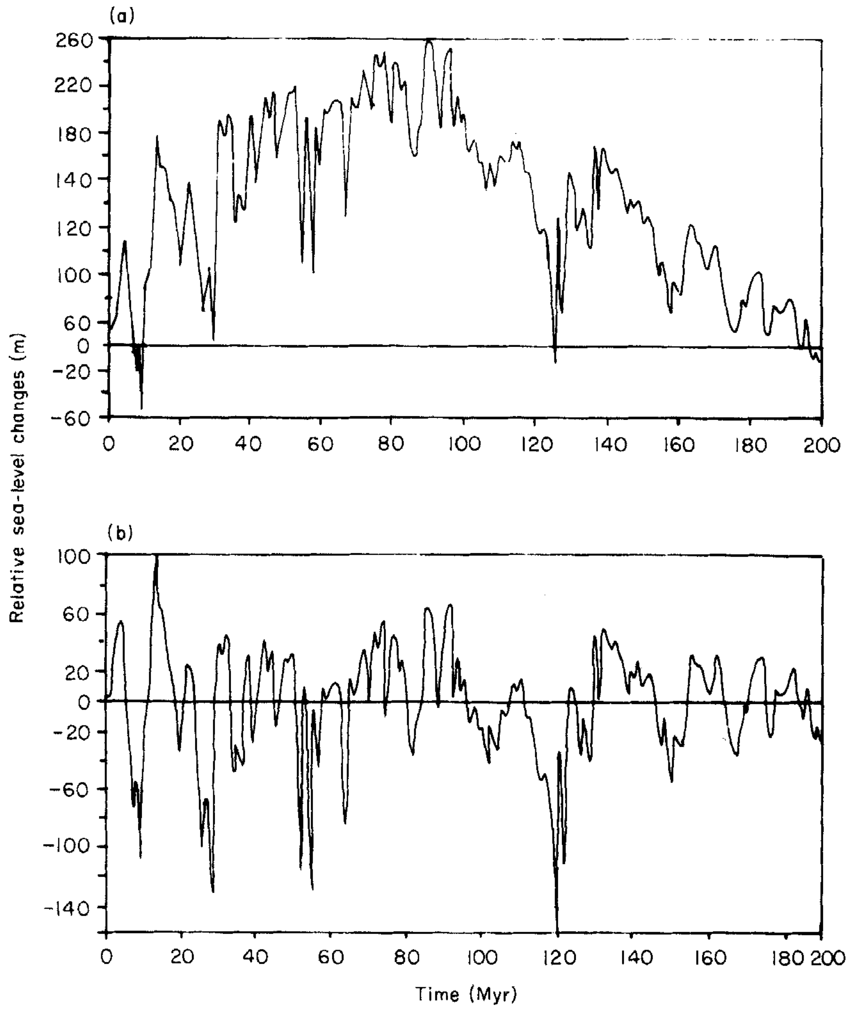

Fig. 2. (a) *Long-term sea-level variation record for the past 200 million years (after Haq* et al., *1987).* (b) *Detrended time series of the above data using 5^{th} degree polynomial.*

spectrum is obtained through iterative processes.

DISCUSSION

A 33 Myr periodicity has been reported in several other geological/geophysical records including biological mass extinctions, impact cratering and low sea levels of the past 250 Myr. Galactic forcing of terrestrial processes has long been suspected (Clube and Napier, 1982). McCrea (1981) has suggested the possible exogenetic forcing of various of the earth's processes including glaciation. McCrea (1975) has also suggested that the passage of the solar system through the spiral arms of the nebula causes terrestrial glaciation. Recently, a new theory has been suggested linking the known periodicities of the Sun's motion in the galaxy with the quasi-periodicities found in various Earth processes (Negi and Tiwari, 1983; Rampino and Stothers, 1984). The periodicity found in the sea-level variation record compares well with the half period (33±3 Myr) of the sun's motion perpendicular to the galactic plane. It may suggest a possible association of long-term sea-level changes with exogenetic processes since no such long-period endogenetic process is well identified.

The theory relating bolide-impacts with biological mass extinction has been widely supported by some workers (Raup and Sepkoski, 1984; Rampino and Stothers, 1984; Alvarez and Muller, 1984). It has also been questioned by others (Officer and Drake, 1985; Courtillot and Cisowski, 1987). The commonly cited terrestrial causes for the mass extinctions include climatic deterioration (Stanley, 1988), sea-level changes (Hallam, 1984) and global volcanism (Officer and Drake, 1985; Pandey and Negi, 1987). There is evidence to suggest that sea-level and climatic changes could be connected with biological mass extinctions. Selective biological mass extinctions may be due to either sea-level fall or subsequent rise. Some of the well known extinction events happened at the time of sea-level lowering and glaciation. These lows are related to climatic deterioration.

CONCLUSIONS

A new spectral technique based on a 'clean' spectral algorithm, is applied for the first time, to analyse long-term sea-level changes of the past 200 Myr. The analysis suggests a stable and dominant spectral peak at 33 Myr. This finding adds to the important possibility of a physical correlation with galactic forcing and marine mass extinctions. The result also corresponds to earlier analyses of various terrestrial cycles among impact cratering, kimberlite intrusions and geomagnetic reversals. Further we may infer that all 33 Myr cycles are governed by a common primary cause of galatic forcing. However, the subject needs much more refined data and studies of possible physical mechanisms before such a theory can be established on a sound basis.

ACKNOWLEDGEMENTS

We are thankful to Mr P.V. Swamy, Ch. Ramaswamy and Shyam Vaidya for their help in preparation of the manuscript. We are also thankful to Drs J. Lehar and J.W. Dreher of MIT, Cambridge for providing us with the computer program listings. The permission accorded to publish this work by the Director, N.G.R.I., Hyderabad is gratefully acknowledged.

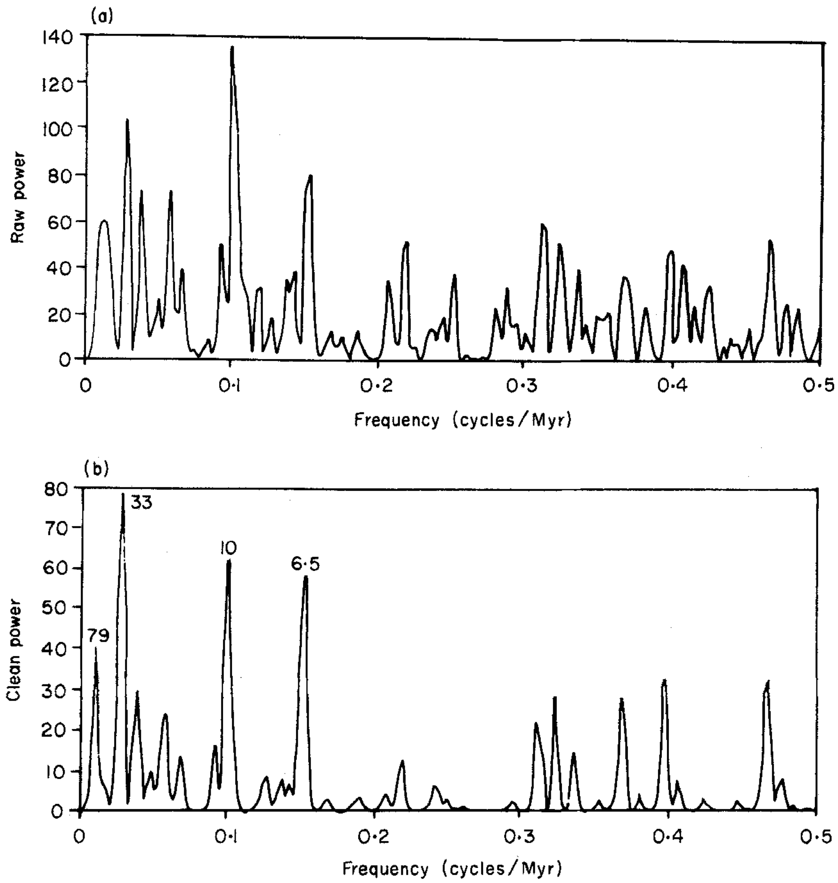

Fig. 3. (a) *Raw Fourier power spectrum of the past 200 million year detrended sea-level variation data.* (b) *Its corresponding power spectrum using 'Clean' algorithm. Details of the computational procedure are described in the text.*

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Received 3 October 1989; accepted 15 January 1990