GEOFIZIKA VOL. 14 1997

Original scientific paper
UDC 551.461.2

Detection of long term modulation orbital cycles in the sea level oscillations using clean algorithm of spectral analysis

R. K. Tiwari, J. G. Negi and K. N. N. Rao

Theoretical Geophysics Group, National Geophysical Research Institute,
Hyderabad, India

Received 30 August 1997, in final form 12 December 1997

The need for a unified astronomical theory of sea-level changes and associated climatic variations motivates the search for Milankovitch eccentricity rhythms in the global sea level variations. The available latest sea level record exhibits long term trend with superimposed higher order frequency oscillations. A new powerful spectral technique based on the one dimensional clean deconvolution algorithm, is applied to the global sea level fluctuations record of the past 30 million years. The spectrum analysis reveals statistically significant (at 90% confidence level) and »clean« cyclicity of 2000 kyr, 1250 kyr, 880 kyr, 660 kyr, 416 kyr, and 260 kyr. Statistically significant sea level cycles indicate possible link with climate and orbital cycles. A principal cycle (E_p) of 413 kyr corresponds to the well known orbital eccentricity cycle. The remaining higher order periodicities are integral multiples of E_p (*e.g.*, $E_p/2$, $3E_p/2$, $2E_p$, $3E_p$, $5E_p$), equivalent to those of the modulation of orbital eccentricity-precession cycles. Matching periodicities of the sea level changes and climatic rhythms, and long term modulation of orbital variations demonstrate significant role of orbital cycles in these processes and integrate the Milankovitch paradigm of orbital forcing to coupled climate-sea level interactions.

Keywords: Sea level oscillations, spectral analysis, clean algorithm.

Introduction

The evolutionary history of the Earth and its various processes can be understood from long term natural records. One such record is the one of fluctuations of the global sea level over time scales ranging from a few thousand years to several million years (m.y.). Evidence gathered by decoding the past remains preserved in the Earth's sedimentary stratigraphic columns/sequences suggests that global sea level have undergone major changes on widely different time scales. These classifications of time scales may also be associated with different physical causes. A recent investigation by Haq et al.

(1987) provided a considerably more accurate sea level variability record which includes a range of low and higher order cycles. Long term sea level change (first order cycles) seems to be associated with plate tectonic processes and may also be linked with cosmic cycles (Negi et al., 1990). However, higher order (cycles) fluctuations superimposed on longer trend, are more prominent in the records of the last 30 m.y. These high frequency oscillations seem to be related to the variations in the continental ice volume which are known to have a dramatic impact on the global sea level. Evidence indicates that during more recent times (*e.g.* Pleistocene, past 2 m.y.), the Earth has undergone simultaneously changes in the volume of its continental ice sheets and the sea level. This distinctive temporal variability has also been associated with variation in solar energy due to changes in the Earth's orbits. The study of possible influence of higher order Milankovitch cycles and modulation of precessional/obliquity frequencies on the microstructure of terrestrial, glacial and sea level catastrophies, may be important for understanding the coupled evolutionary history of possible linkages of climate sea level changes and orbital cycles during the Neogene period.

Evidences of orbital cycles in various climate and sedimentary records have been invariably suggested by several workers (Hays et al., 1976; Olsen, 1986t; Muller and MacDonald, 1987a, b). However, due to lack of mechanism involved in clearly explaining the role of orbital cycles, particularly eccentricity cycles in the climate record, the reactions from climate modellers and sedimentologists have been skeptical (Algeo and Wilkinson, 1988). This conflict further widens with recent data analysis from the Devils Hole carbonate, which has indicated that the terrestrial record of climate changes was not in synchrony with marine record. We mention here, however, that researchers have used more sophisticated record and method of analysis to maintain that orbital cycles do play significant role in modulating climate/sedimentary environment, sea level changes *etc*. (deBoir and Smith, 1994). Also recent studies suggest that the marine and terrestrial records are indeed in synchrony and that the Devils Hole record is only a local anomaly (Kerr, 1997; Edward et al., 1997).

If an abrupt and non-linear behaviour of glacial and deglacial processes (slow growth and rapid melting) are in some way linked to the sea level changes, it might lead to a non-linear response of sea level variability too. During the past two decades, various spectral analyses of evolutionary palaeoclimatic time series dealing with geochemical and glacial and interglaciation cycles and associated sea level changes have brought out remarkable advances in our understanding of coupled geoastronomical relationships. The Fourier spectral techniques applied to these apparently non-linear time series greatly hinder unequivocal differentiation and statistical confirmation of apparent cyclic pattern in geological records. In addition to this in many situations the time series are recorded at unevenly spaced time intervals. For such time series the traditional Fourier spectral analysis is corrupted by the interference of peaks due to convolution of discrete Fourier transform with the so called spectral window (Robert et al., 1987). Resulting peaks therefore make it quite difficult to suggest proper physical interpretation. A non-linear spectral analysis which is based on the clean algorithm renders a more reliable and stable spectral picture of the physical processes. Clean algorithm removes artifacts introduced by missing data and sampling errors. The resolving capability of the clean method on real astronomical record has been emphasized and demonstrated by Dreher et al. (1986) and Duvall and Harvey (1984). The clean deconvolution algorithm (Robert et al., 1987) has also been applied to long term sea level record and to the secular variation of dolomite abundance in deep marine sediments (Negi et al., 1990, 1996). The purpose of our earlier sea level data analysis (Negi et al., 1990) was to identify long term cycles, if any, of cosmic origin.

The main objective of the present work is to examine higher order frequency oscillations of Earth's orbital Milankovitch cycles superimposed on the main larger secular cycles. These high frequency oscillations, the so called third order wiggles, (Haq et al., 1988) are more clearly evident during the past 30 m.y. Although there has been some criticism of sea level record (Miall, 1997) produced by Haq et al. (1987), we believe that this is one of the best and most comprehensive long term sea level records as yet available, which can be appropriately used for a meaningful time series analysis. We also mention here that in order to maintain the comparative status with similar work done earlier, we have deliberately chosen this record and a new method of spectral analysis.

We demonstrate here (i) the applicability of clean spectroscopy on the best available data set of global sea level fluctuation in the past 30 m.y., (ii) discuss the results in terms of long term modulation of eccentricity-obliquity-precession beats cycles, and (iii) compare our results with already published results of comparable periodicities on this time scale.

Clean algorithm of spectral analysis

The clean algorithm of spectral analysis has been successfully applied to the unequally spaced astronomical time series for detecting periodic components (Robert et al., 1987). The clean algorithm is based on a complex one dimensional version of the clean deconvolution algorithm widely used in two dimensional image reconstruction. We briefly describe the method for uninitiated readers.

The Fourier transform of the sampled signal is the convolution of the spectrum with the spectral window function *i.e.*,

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

where $D(\nu)$ and $W(\nu\,)$ are the raw spectrum and the spectral window function respectively, and F(ν) is the Fourier transform of the time function $f(t)$. The symbol $*$ represents convolution. $D(\nu)$ and $W(\nu)$ can be calculated directly from the sampled data and are given by:

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

and

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

Consider a single harmonic component (cosinusoid) with harmonic amplitude A, frequency ν', and phase constant φ' to apply 'clean' to the deconvolution of equation (1).

The spectrum of this signal is $F(\nu) = a\delta(\nu - \nu') + a^* \delta(\nu + \nu')$ where $a = A/2$ $e^{-i\varphi}$ and the time function is given by:

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

Given the frequency of a clean component estimated from the raw spectrum, its complex amplitude a is given by Robert et al. (1987):

$$a(D;\nu) = [D(\nu) - D^*(\nu) W(2\nu) / 1] - |W(2\nu)|^2 \tag{4}$$

where * represents complex conjugate.

The chief objective of the procedure is to estimate $F(\nu)$ in equation (1) from the knowledge of $D(\nu)$ and $W(\nu)$. This is done according to the following iterative procedure.

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

$$C^i = ga(R^{i-1}; \nu^i) \tag{5}$$

where a is the same as in equation (4) and C^i, is the i-th clean spectral component, g is a clean gain factor (typically the value of g lies between 0.1 and 1) and R^{i-1} is the i-th residual spectrum. A fraction g of the spectral component is subtracted to prevent errors from destabilizing the clean procedure. A reasonable degree of stability can be ensured if the value of g is taken to be 0.5. In general, the iterative process for the i-th residual component is given by:

$$R^{i}(\nu) = R^{i-1}(\nu) - [C^{i}W(\nu - \nu') - (C^{i})^{*}W(\nu - \nu')] \tag{6}$$

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

2. The iterative procedure is repeated using equation (6) to obtain successive approximations, *i.e.,* R^1, R^2, ..., R^N. After completion of the N-th step we have a set of N spectral clean components and the residual spectrum R^N.
3. The spectral clean components obtained are convolved with the clean beam $B(\nu)$ in order to make the frequency resolution of the clean spectrum. B has a Gaussian shape of amplitude $B(0) = 1$ and a linear slope in phase chosen to fit the central peak of $W(\nu)$.
4. Finally the clean spectrum $S(\nu)$ is given by:

$$S(\nu) = \sum_{i=1}^{k} [C^{i}B(\nu - \nu') + (C^{i})^{*}W(\nu + \nu')] + R^{k}(\nu), \tag{7}$$

where k is number of clean components.

Global sea level fluctuation record for the past 30 m.y.

Vail et al. (1977) used stratal geometry and patterns of onlap, downlap, truncation and basinward shifts of coastal onlap to interpret sea level history along various continental margins. However, the application of concept of sequence stratigraphy to outcrop sections has provided the framework to identify and classify major, medium and minor sequences also. In earlier analysis minor sequences were generally beyond the resolution obtainable with seismic data but they can be mapped by detailed well log studies and in outcrop sections. Haq et al. (1988) published considerably more accurate and precise sea level record which includes higher order cycles too. The new data set used in this study (Haq et al., 1988) is based on recognition of depositional sequence in outcrop and well logs in addition to original seismic stratigraphy data of Vail et al. (1977). The new generation of cycle charts of sea level fluctuations are considerably improved version over previously published record which was based entirely on sub-surface information. The sequence stratigraphic depositional model, together with detailed paleontological data, enhance the ability to recognize genetically related sediment packages in outcrop section.

According to Haq et al. (1988) the changes of relative sea level, which is the combined effect of subsidence and eustacy, control the accommodation potential of the sediments and distribution of facies within the system tracts. In marine outcrops three depositional surfaces can be identified. They are: (i) transgressive surface, (ii) the surface of maximum flooding which is referred to as the downlap surface on seismic profiles and (iii) the sequency boundary *i.e.* downward shift of coastal onlap. Monitoring the long term sea level record using the concept of depositional surface means considering envelope of set of accurately determined higher order sea level changes (Haq et al., 1987). The sea level fluctuation record is reproduced in Figure 1 (top). According to Haq et al. (1987), the time scale is well correlated by multiple dating techniques including magnetostratigraphy, chronostratigraphy and biostratigraphy. There is some controversy regarding minor fluctuations in the data (Gradstein et al., 1988; Mathew, 1988). It is, however, maintained that these smaller sequences are accurately resolved and the available data is possibly the best interpretable record available (Haq and Vail, 1988). We anticipate, however, that the sedimentary record due to poor dating might include a fair amount of noise which is inescapable. This implies that we can not expect to find a perfect one-to-one frequency (periodic) correlation between the different related phenomena.

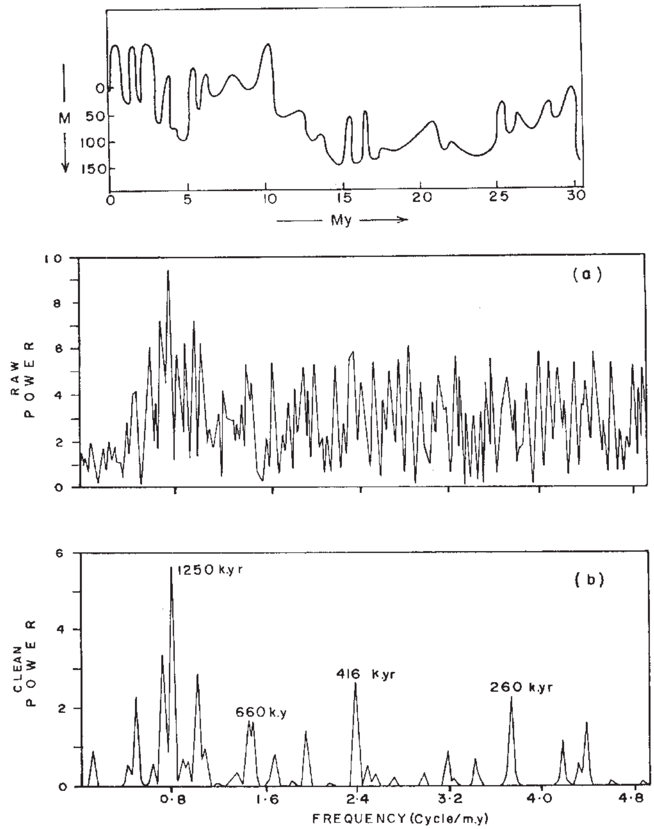

Figure 1. Analysis of actual sea level changes data (top) and (a) Fourier spectrum (b) Clean spectrum.

Clean spectroscopy of the sea level time series

Visual inspection of the sea level changes record apparently indicate a relatively more frequent variability for the past 10 m.y. than in the earlier part. Keeping in view the non-stationary behaviour of these records, it is prudent to divide time series into appropriately different small sub-time series and perform the spectral analysis by presuming that the smaller segments are stationary. Spectral analysis presented here is based on such assumption, albeit in strict sense this theoretical assumption may not be valid.

In the traditional Fourier analysis the highest frequency (Nyquist frequency) present in the data set is defined as $l/2\Delta t$ where Δt is the uniform sampling interval. Clean algorithm method of spectral analysis accepts unevenly spaced data series where the minimum sampling interval $\Delta t_{\min}$ in available data set may be taken as the Nyquist frequency. The Nyquist frequency is then defined as $f = 1/2\Delta t_{\min}$. A major disadvantage encountered in the fast Fourier analysis is that zero value is assumed at points where data is sparse or missing. It also produces biased peaks where large gaps are present in geological records. In contrast, the clean algorithm interpolates across missing data points in frequency domain and produces more stable peaks through the process of iterations. In the present analysis, we have taken the minimum sampling time Δt as 100 kyr. Thus, the shortest periodicity which can be detected here is 200 kyr. First we analyzed the total time record. The Fourier and clean spectra of the sea level time series are displayed in Figures 1a and 1b respectively. It is clearly evident from Fourier spectra (Figure la), that there are several instance of splitting and clustering of spectral peaks possibly due to the presence of non-linearity and noise in the record. Fisher's statistical reliability test (Shimsoni, 1971) of Fourier spectral peaks, however, indicates that some of these peaks (notably centered around 1250 kyr, 880 kyr, 660 kyr, 413 kyr and 260 kyr) are significant at confidence level of more than 90%. The numerical stability of these spectral peaks has been examined using the clean algorithm discussed in previous sections. Following Robert et al. (1987), appropriate measures that have been taken in the computation of the clean spectrum are: i) a 'noise' value has been determined from the raw spectrum and the maximum of R^{N} residual spectrum computed is kept smaller than this value. ii) Stable spectral peaks are obtained by choosing adequate number of iterations. The results exhibit stable and clean higher order peaks corresponding to periods/bands of 1250 kyr, 880 kyr, 660 kyr, 416kyr and 260 kyr. In the second step, we have varied the bin-width and checked the stability of these peaks. It is interesting to note that for three such sets the above peaks are remarkably consistent (Figure 2).

In the third step, the time series is divided into two subsets, *i.e.* from 0 to 10.13 m.y. and from 10.13 to 29. 895 m.y. and similar analysis was repeated. The clean spectra of the first part of the record *i.e.* 0–10.13 m.y. reveal domi-

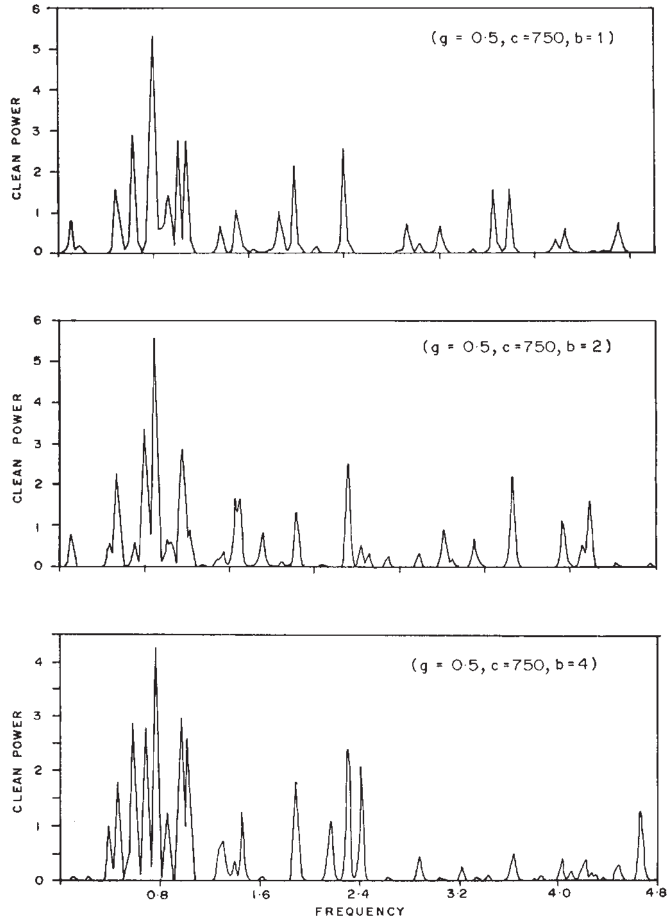

Figure 2. Clean spectra for various bin widths.

nant peaks at around 1.23–1.04 m.y., 800–650 kyr, 400 kyr, 250 kyr and 220 kyr (Figure 3). Second part of the sea level record *i.e.* 10.13 m.y.–29.85 m.y. reveal clean peaks at 1.27–1.07 m.y., 840 kyr, 500 kyr, 400 kyr (Figure 4). The analysis indicates that these cycles dominate the climate and sea level records throughout the Miocene and even beyond which is discussed in the next section. We might, however, note some obvious differences in results of the analyses of the 0–10 m.y. record and the 10–30 m.y. record. These differences may possibly arise due to the fact that age control on the sea level curve diminishes further back (before 10 m.y.) in time due to the lack of more accurate age dating techniques. The older Tertiary record may not be detailed enough to reveal or resolve the spectral peaks that the 0–10 m.y. record does.

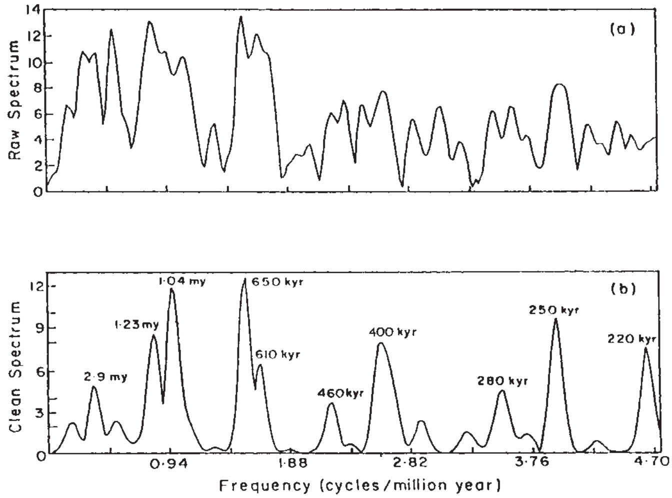

Figure 3. (a) Fourier and (b) Clean spectra of 0–10 m.y. sea level change record.

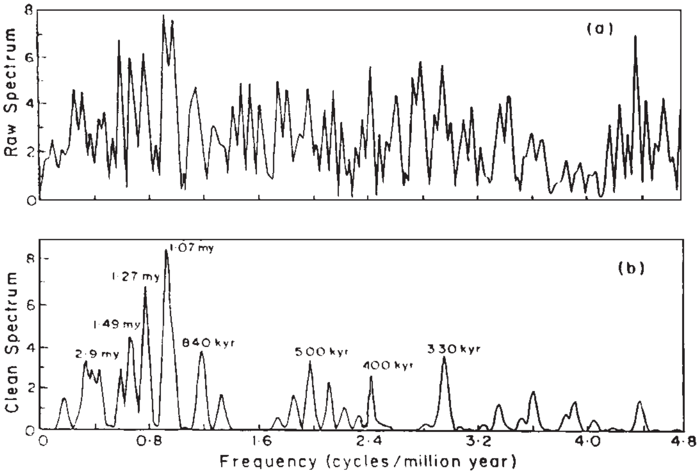

Figure 4. (a) Fourier and (b) Clean spectra of 10–30 m.y. sea level change record.

Discussions

Variations in the Earth's orbital elements and consequent changes in the solar energy input (Milankovitch, 1941) exert direct or indirect influence on the oceanic and atmospheric circulation patterns, the distribution of climatic zones, sedimentation patterns, biogenic productivity, dissolution of carbonate and other associated phenomena (Berger, 1989). The important cycles in this process deal with the longitude of the perihelion with respect to the vernal equinox (precession cycles of about 23 and 19 kyr), the tilt of the Earth axis (obliquity cycle of about 41 kyr), and eccentricity of the Earth's orbit with main cycles of about 100 kyr and 413 kyr. The eccentricity modulates the yearly amount of total solar energy received by the whole Earth. The effect of obliquity is prominent at high latitudes and almost negligible at low latitudes. Precessional cycles control the timing of the seasons at any latitude with respect to the Earth–Sun distances and, therefore, the magnitude of this effect is proportional to the eccentricity of the Earth's orbit. Besides these well known Milankovitch cycles, there are higher order beat cycles and combination tones of these cycles which possibly arise from nonlinear interactions of various orbital terms.

Table 1 provides the correlation of various sea level periodicities with similar periodicities in some other geophysical time series. Higher order periodicities (2000 kyr, 1200 kyr, 800 kyr, 600 kyr) have been reported in climate and the stratigraphy records *e.g.* in palaeo-oceanic and climate records (Tiwari 1987a, b), in the range of 790 to 860 kyr record (Park and Herbert, 1987), and in the range of 600 to 750 kyr (Tenkate and Sprenger, 1989). Van Tassel (1987) has also reported similar cyclicity in calcilutite marl succession in the S.E. Spain and carbonate/insoluble residue ratios of hemipelagic. Evidence of higher order periodicities has also been suggested in mesoscale Phanerozoic sedimentary rhythms (Algeo and Wilkinson, 1988). Recently Hein et al. (1992) and Negi et al. (1993) suggested higher order orbital cycles in ferromagnese-crust of the Pacific Ocean and short term reversals wiggles, respectively (Table 1). It is also interesting to note that Olsen (1986) analyzed one of the best and exquisitely detailed sedimentary record of the orbital variation decoded from Triassic lake sediments. This analysis clearly reveals the cyclicity of the order of 100 kyr, 1.2 m.y. and 2 m.y. The present analysis also clearly brings out stable peaks of 400, 660, 880 and 1250 kyr. The range for all cycles corresponds well to the range of periods of the Earth's orbital parameters as predicted by the Milankovitch insolation theory (Berger, 1977).

The higher order periodicities found in the climate and sea level changes records closely match the theoretical estimates of eccentricity beat cycles (Berger, 1977). This provides strong empirical evidence of orbital forcing or their control over stratigraphic patterns in the past geological time. Although the physical link between climate and sea level changes may be more intricate and need more explanation, a clear evidence of orbital periodicities in the climate record and sea level obviously indicate that both processes are governed by a common cause. Glacial and deglacial cycles also substantially modify the sea level fluctuations on a global scale (Heckel, 1986; Mathew and Poore, 1980; Hodell et al., 1986). Cyclic patterns of minor (40 to 120 kyr) and major (235 to 400 kyr) cycles in the sea level record have been observed by Fischer (1964), Goldhammer et al., (1987), Grotzinger (1986). The 400 kyr cycle corresponds to the principal eccentricity cycles (E_p) of the orbital variations. Interestingly, the high frequency sea level oscillations may also be linked to the compound and amalgamated periods of lower order eccentricity as well as to higher order eccentricity cycles (*e.g.*, $E_p/2$, $3E_p/2$, $2E_p$, $3E_p$, $5E_p$).

Recently Luc-Beaufort (1994) has related higher order cycles identified in marine climate record of Miocene periods as a possible result of long term modulations of eccentricity and obliquity parameters. Luc-Beaufort (1994) performed spectral analysis on two palaeocenographic time series for the past 10 m.y. His analysis revealed a number of possible cycles of order of 3.39 m.y., 2.30 m.y., 2.170 m.y., l.615 m.y., l.20 m.y., l.164 m.y., l.14 m.y., 0.86 m.y. and 0.780 m.y. He interpreted these frequencies in terms of modulation of eccentricity and obliquity cycles. Table 2 summarizes the different views and explanations of higher order orbital cycles and the correlation with sea level changes periodicities. In view of striking similarities of our periodicities in the sea level changes and orbital periodicities, we also suggest a combined

Table 1. Correlation of sea level periodicities with similar periodicities in other geophysical records

Periodicities in global sea level (This paper) (kyr)	Climate (Tiwari, 1987) (kyr)	Geomagnetic reversals beat Negi et al. (1993) (kyr)	Ferromagnese crust Hein et al. (1992) (kyr)
2000	–	–	2040
1250	1270	1310	1310
880	980	800	800
660	–	–	–
416	416	400	–
260	200	–	–

Table 2. Correlation of sea level periodicities with different version of orbital cycles

Sea level change (This paper) (kyr)	Eccentricity Berger (1977) (kyr)	Beat period Stothers (1987) (kyr)	Obliquity/eccentricity beat Luc Beaufort (1994) (kyr)
2000	2035	2031	2380
1250	1233	1282	1140
880	–	–	800
660	600	604	–
416	413	413	–
260	260	–	–

role of orbital as well as modulation cycles of orbital variations in these processes. There could be two possible interpretations of the 1250 kyr cycle that appears in the clean spectra. First, it could be simply the integral multiple of 412 yr, eccentricity component (3 × 412 kyr), which also (1333 kyr) appears in eccentricity expansion series (Berger, 1977). The second possibility could be that several weak cycles in sea level and climate records are the result of non-linear interactions of precessional cycles. Thus it might also appear as a beat cycle due to non-linear interactions of two precessional cycles of 23.716 kyr and 23.23 kyr. In addition to this, two other sets of precessional cycles *e.g.* $t = 18.76$ kyr and $t = 19.1555$ kyr will produce dominant non-linear periodicity of 2 m.y. which is also equivalent to eccentricity cycles (Berger, 1977). The beating phenomena of the two very close precessional frequencies (Wigley, 1976) or non-linear glacial-interglacial response to periodic forcing may possibly produce higher order sea level periodicity.

Besides the above interpretations, we also suggest that dominant periodicities of 416 kyr and 880 kyr cycles in the sea level data, may possibly be related to the basic eccentricity cycles of the Earth's orbit. Although the explanation for the role of these eccentricity cycles in climate system and sea level processes are debated (Pollard, 1982; Wigley, 1976; Ghil and Letreut, 1981; Letreut and Ghil, 1983), modern theoretical climate models (Benzi et al., l982; Nicolis, 1982) demonstrate the possibility of amplification of the eccentricity signal by the climatic system itself. The external forcing due to orbital variations and internal stochastic mechanism could amplify the forcing effect on long term alterations of climate and sea levels.

Conclusions

A new spectral technique based on the one dimensional clean deconvolution algorithm is applied to the global sea level changes record of the past 30 m.y. Some significant findings are the following:

(i) Analysis of the sea-level record resolves clean periodicities of 1250 kyr, 880 kyr, 660 kyr, 416 kyr and 260 kyr. These are identical to the theoretically estimated higher order eccentricity and modulation of precession-obliquity-eccentricity cycles.

(ii) The presence of long term modulation of eccentricity and modulating cycles in the sea level and climate records support the Milankovitch theory of the sea level and climatic changes.

(iii) The accurate geological data on sedimentary rhythms and glaciation/deglaciation records will be useful in identifying smaller orbital periods.

(iv) The clean algorithm is an appropriate tool for the analysis of the unevenly and broadly distributed stratigraphic sequences. The technique has a great potential for application in analyses of other geophysical time series.

Acknowledgements – We are grateful to Dr. B. U. Haq for providing large scale sea level variation record. We are thankful to Mr. V. Subrahmanyam for his help in preparation of the manuscript. The permission granted by the Director of the National Geophysical Research Institute, Hyderabad, to publish this work is gratefully acknowledged.

References

Algeo, T. J. and Wilkinson, B. H. (1988): Periodicity of mesoscale phanerozoic sedimentary cycles and the role of Milankovitch orbital modulation, J. Geology, **1996**, 313–322.

Benzi, R., Parisi, G., Sutera, A. and Vulpiani, A. (1982): Stochastic response in climatic change, Tellus, **34**, 10–16.

Berger, A. L., (1977): Support for the astronomical climatic change, Nature, **269**, 44–45.

Berger, A. (1989): The spectral characteristics of Pre-Quarternary climate records: An example of the relationship between the astronomical theory and Geosciences in climate and Geosciences, 47–76. Eds (A. Berger et al.). *In:* Climate and Geosciences: A challenge for science and society in the 21th century. Kluwer Academic publishers.

Dreher, J. W., Robert, D. H. and Lehar, J. (1986): Very large array observations of rapid non-periodic variations in OJ287, Nature, **320**, 239–242.

Duvall, Jr. T. L. and Harvey, J. W. (1984). Rotational frequency splitting of solar oscillations, Nature, vol. 310, 19–22.

Fischer, A. G. (1964): The Lofer cyclothems of the Alpine Triassic, *in:* Merriam D. F. (Ed.) Symposium on cyclic sedimentation: Kans. State Geological Survey Bull., **169**, (1), 107–149.

Ghil, M. J. and LeTreut, H. (1981): A climate model with cryodynamics and geodynamics, J. Geophys. Res., **86**, 5262–5270.

Goldhammer, R. K., Dunn, P. A. and Hardie, L. A. (1987): High frequency glacio-eustatic sea level oscillations with Milankovitch characteristics recorded in middle Triassic Platform carbonates in Northern Italy, Am. J. of Science, **287**, 853–892.

Gradstein et al. (1988): Comments on paper by Haq et al. (1987) **235**, 1156–1167, Science, **241**, 1601, 1988.

Grotzinger, J.P. (1986): Cyclicity and palaeo-environmental dynamics, rocknest platform, Northwest Canada, Geol. Soc. Am. Bull., **97**, 1208–1231.

Haq, B. U., Hardenbol, J. and Vail, P. R. (1987): Chronology of fluctuating sea levels since the Triassic, Science, **235**, 1156–1167.

Haq, B. U. and Vail, P. R. (1988): Hardenbol, J. and Van Wagoner, J.G., Reply to the comments by Haq et al., Science, **241**, 596–597.

Heckel, P.H. (1986): Sea level curve for Pensylvanian eustatic marine transgressive-regressive depositional cycles along mid-continent outcrop belt, North America, Geology, **14**, 330–334.

Hein, J. R, Bohrson, W. A., Schulz, M. S., Noble, M. and Clague, D. A. (1992): Variation in the time scale composition of a central feromagnese crust: Palaeoceanographic implications, Palaeoceanography, **7**, 63–77.

Herbert, T. D. and Fischer, A. G. (1986): Milankovitch climatic origin of Mid Cretaceous black-shale rhythms in central Italy, Nature, **321**, 739–743.

Hodell, D. A., Elmstrom, K. M. and Kennett, J. P. (1986): Latest Miocene changes of global ice volumes, sea level changes and the messinian salinity crisis, Nature, **320**, 411–414.

LeTreut, H. and Ghil, M. J. (1983): Orbital forcing, climatic interactions and glaciation cycles, J. Geoph. Res., **8**, 5167–5190.

Luc-Beaufort (1994): Climate importance of the modulations of the 100 kyr cycle inferred due to 16 m.y. long Miocene records, Palaeoceanography, **9**, 821–834.

Mathew, R. K. and Poore, R. J. (1980): Tertiary D^{18}0 record and glacioeustatic sea level fluctuations, Geology, **8**, 501–504.

Mathew, R. K. (1988): Comments on paper by Haq et al. (1987), Science, **235**, 1156–1167, Science, **241**, 597–599.

Milankovitch, M. (1941), Kanon der Erdbestrahlung, R. Serbian Acad. Special Publ. 132. Sect. Math. Nat Sci., **33**. (Canon of Insolation and the ice age problem, English translation by Israely program for Scientific translations, Jerusalem, 1969).

Negi, J. G. and Tiwari, R. K. (1984): Periodicities of palaeomagnetic and palaeoclimatic variations: a Walsh spectral approach, Earth and Plan. Sci. Lett., **70**, 137–147.

Negi, J. G., Tiwari, R. K. and Rao, K. N. N. (1990): Clean spectral analyses of long term sea level changes, Terra Nova, **2**, 138–141.

Negi, J. G., Tiwari, R. K. and Rao, K. N. N. (1993): Comparison of Walsh and Fourier spectroscopy of geomagnetic reversals and non-sinusoidal palaeoclimate time series, IEEE Trans. on Geoscience and Remote Sensing, **31**, l27–135.

Negi, J. G., Tiwari, R. K. and Rao, K. N. N. (1996): Clean periodicity in secular variation of dolomite abundance in deep marine sediments, Marine Geology, **133**, 113–121.

Nicolis, C. (1982): Stochastic aspects of climatic transitions response to a periodic forcing, Tellus, **34**, 1–9.

Park, J. and Herbert, T. D. (1987): Hunting for palaeoclimatic periodicities in a geological time series with an uncertain time scale, J. Geoph. Res., **92**, 14027–14040.

Pollard, D. P. (1982): A simple ice sheet model yields realistic 100 kyr glacial cycles, Nature, **287**, 430–432.

Robert, D. H., Lehar, J and Dreher, J. W. (1987): Time series analysis with clean, I. Derivation of spectra, Astronomical J., **93**. 968–989.

Stothers, R. B. (1987): Beat relationship between orbital periodicity in insolation theory, J. Atmospheric Sciences, **44**, 1875–1876.

Tenkate, W. G. and Sprenger, A. (1989): On the periodicity in a calcilulite-marl succession (SE-Spain) Cretaceous Research, **10**, 1–31.

Tiwari, R. K., (1987a): Higher order eccentricity cycles of the late and mid miocene climatic variations, Nature, **327**, 219–221.

Tiwari, R.K. (1987b): A Walsh spectral comparison of oxygen (D^{13}O) and carbon isotope (D^{13}C) variations of the pleistocene borehole (EUREICA 67-135) from the Gulf of Mexico and their orbital significance, Marine Geology, **78**, 167–174.

Van Tassell, J. (1987): Upper devonian Catskill Delta margin cyclic sedimentation: Brallien Scherr, and Foreknobs Formations of Virginia and West Virginia, Geol. Soc. Am. Bull., **99**, 414–426.

Wigley, T. M. L. (1976): Spectral analysis and astronomical theory of climate change, Nature, **264**, 629–631.

SAŽETAK

Detekcija dugoperiodički moduliranih orbitalnih ciklusa oscilacija morske razine pomoću čistog algoritma spektralne analize

R. K. Tiwari, J. G. Negi i K. N. N. Rao

Potreba za jedinstvenom astronomskom teorijom promjene morske razine i s time povezanih klimatskih varijacija motivira traženje Milankovićevih ekscentričnih ritmova u globalnoj varijaciji morske razine. Najnoviji raspoloživi podaci o razini mora pokazuju dugoperiodički trend sa superponiranim oscilacijama višeg reda. Nova moćna spektralna metoda bazirana na čistom dekonvolucijskom algoritmu primijenjena je na podatke o kolebanju razine mora tijekom zadnjih 30 milijuna godina (m.a.). Tako su opažene statistički značajne istaknute komponente perioda 2.000 m.a., 1.250 m.a., 0.880 m.a., 0.660 m.a., 0.416 m.a. i 0.260 m.a, koje bi mogli biti u vezi s klimatskim i orbitalnim periodičkim promjenama. Glavna komponenta (E_p) od 0.416 m.a. odgovara dobro poznatoj orbitalnoj komponenti od 0.413 m.a. Ostale komponente cjelobrojni su višekratnici od E_p ili $E_p/2$ te odgovaraju orbitalnim komponentama u vezi s eksentričnosti i precesijom. Poklapanje periodičnosti kolebanja razine mora i klimatskih promjena s dugoperiodičkim modulacijama orbitalnih ciklusa ukazuje na veliku ulogu orbitalnih ciklusa u tim procesima.

Corresponding author's address: R. K. Tiwari, Theoretical Geophysics Group, National Geophysical Research Institute, Uppal Road, Hyderabad 500007, India