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A 2,200 years periodicity in the Asian monsoon system

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Abstract. We have carried out a high-resolution study of fluctuations in upwelling intensity along the Oman Margin, western Arabian Sea, through the last 19,130 years based on several marine microfossil indices of upwelling. We document a periodicity of 2,200 years in the upwelling indices, which would be governed by the south-west (SW) monsoon with such a periodicity. Our data further demonstrate greater amplitude in the variability of the SW monsoon during the Holocene than during the last glacial period. Our reported 2,200 years periodicity has two implications (1) oceanic circulation changes partly influence monsoon strength at sub-Milankovitch cycles (2) previously documented 2,300 years periodicity in atmospheric ^{14}C might be induced by oceanic circulation changes.

Introduction

The SW monsoon system in the Arabian Sea exerts a strong influence upon the climatic conditions in south and southeast Asia, and the associated monsoon rainfalls have great impact on the socio-economic and agricultural development in the densely populated south Asia. Seasonal variation in the heating of the southern Asian continent produces a seasonal reversal in the wind direction in the Arabian Sea [*Wyrtki*, 1973]. During summer (June through September) the SW monsoon winds are most vigorous and drive intense upwelling off Oman and Somalia, which promotes very strong phytoplankton productivity in the western Arabian Sea. Reversal of the wind system during the winter (north-easterly monsoon) supresses the upwelling and lowers the productivity in the western Arabian Sea. The SW and NE monsoon winds thus produce a seasonal contrast in the primary productivity and seasonal dominant lithogenic and biogenic fluxes to the deep sea [*Nair et al.*, 1989] forming an integrated geological record of upwelling. Thus the history of monsoon variations may be monitored through studies of fluctuations in upwelling intensity in the western Arabian Sea. Quaternary paleoclimatic records and climate simulation models have shown that the intensity of the SW monsoon in the Arabian Sea fluctuates with periodicities of 100,000 and 23,000 years, which correspond to periods of glacial and interglacial cycles and precessionally driven Northern Hemisphere summer insolation, respectively [*Prell*, 1984; *Prell and Kutzbach*, 1987; *Anderson and Prell*, 1993]. Recently, it has been shown that the monsoon climate is affected by abrupt climatic changes [*Sirocko et al.*, 1993]. In this paper we present evidence of a 2,200 years periodicity in the Asian monsoon system.

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Samples and Methods

We studied ODP Site 723A from the Oman Margin (18°03'N, 57°37'E; water depth 807.8 m) through the last 19,130 years (latest Pleistocene and Holocene) with the objective of tracing the variability in the strength of the SW monsoon. The rate of sedimentation was 31-40 cm/1000 years during the Holocene and 34-69 cm/1000 years during the last glacial period and was thus extraordinarily high for continenatl slopes. This site, therefore, provides a high-resolution record of upwelling history from the last glacial to Holocene period (our average time resolution is 250 years). The planktonic foraminifer species *Globigerina bulloides* has been used to monitor the Quaternary upwelling history in the Arabian Sea [*Prell*, 1984; *Anderson and Prell*, 1993]. We analyzed relative abundances and accumulation rates of *G. bulloides* (number of specimens/g sediment/1000 years), and overall accumulation rates of planktonic foraminifera (Figure 1), which represent indices of the strength of upwelling and the associated intensity of the SW monsoon in the Arabian Sea [*Curry et al.*, 1992., *Anderson and Prell*, 1993]. A time series containing 90 equally-spaced observations at intervals of 200 years in the time interval between 1,200 and 19,200 years BP was created using cubic-spline interpolation of initial agc estimates based on the radiocarbon chronology (Table 1). We employed Singular Spectrum Analysis (SSA) [*Broomhead and King*, 1986; *Vautard et al.*, 1992] to analyze the dominating signals in the time series. The formulation of *Broomhead and King* [1986] was employed to estimate the covariance matrix. Replicate analyses of SSA using different Δt's and embedding dimensions confirm the reproducibility of the SSA results presented here.

Results and Discussion

SSA of mass accumulation rates of *G. bulloides* indicates that the first four eigenvalues λ_1-λ_4 stand out above the remaining eigenvalues and are interpreted as significant (Figure 2A). These eigenvalues account for 74% of the variance in the embedding space. The occurrence of pairs of eigenvalues λ_1-λ_2 and λ_3-λ_4 above the noise floor is interpreted in terms of strong deterministic components in the signal [*Vautard and Ghil*, 1989]. The corresponding Empirical Orthogonal Functions (EOFs or eigenvectors in standard principal component terminology) indicate that the first pair of eigenvalues (λ_1-λ_2) accounting for 62% of the variance, is related to a trend in the time series, and the second pair (λ_3-λ_4) accounting for 12% of the variance to a periodicity of 2,200 years (Figure 2B). Hence, SSA partials out those portions of the variability in the time series that are due to trend and an oscillatory behavior. The first four reconstructed components (RCs 1-4) recover major portions of the variability in the original time series (Figure 2C). High resolution Multi Taper Method (MTM) spectral analysis confirms the existence of a 2,200 years periodicity in this record. SSA of the relative abundances of *G. bulloides* and

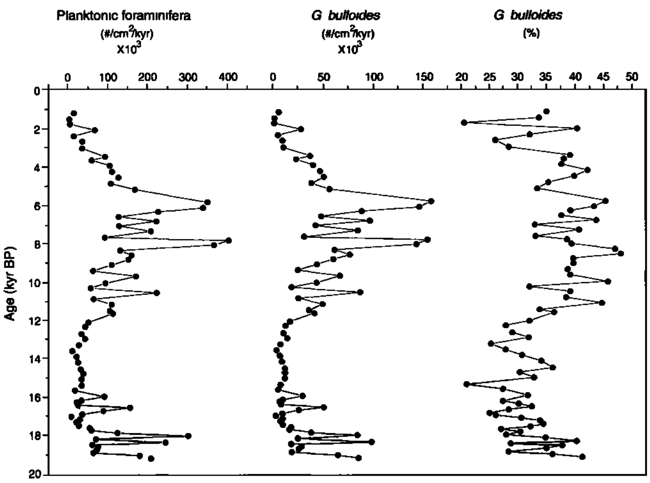

Figure 1. Variations in mass accumulation rates of planktonic foraminifera, *G. bulloides* and relative abundances (percentages) of *G. bulloides* through the last 19,130 years in ODP Site 723A from the western Arabian Sea. These microfossil indices are sensitive to upwelling intensity and may, therefore, be employed to monitor the late Quaternary history of the SW monsoon climate in the Arabian Sea.

total mass accumulations of planktonic foraminifera exhibit similar results (not shown here).

The records of RC1 and 2 for all three variables indicate increasing upwelling begining in the latest Pleistocene (about 12,000 years BP) and reaching a maximum at 9,000-6,000 years BP (Figure 3). From that time the upwelling indices decreased rapidly to low values during the last few thousand years. This suggests stronger monsoon activity during the early Holocene and weaker intensity during the final stages of the last glacial period. This observation is consistent with other monsoonal variability records in the Arabian Sea [*Duplessey*, 1982; *Prell*, 1984]. The increase in the SW monsoon at about 12,000 years BP corresponds to the maximum rate of the ice-sheet melting in the Northern Hemisphere [*Fairbanks*, 1989]. The monsoon intensity was at its peak from 9,000-6,000 years BP and then started to decline until 1,200 years BP, which exactly mirrors the fluctuations in Indian lake levels [*Swain et al.*, 1983].

The 2,200 years periodicity exhibited by EOFs 3 and 4 (Figure 2B) is superimposed upon the major trend in the data (RCs 3 and 4 are shown in Fig. 4). The amplitude of the SW monsoon variations is much higher during the Holocene than during the last glacial period (Figure 4). Several other sets of data, like tropical lake levels [*Street and Grove*, 1979], lake levels in India [*Swain et al.*, 1983] and pollen data [*Van Campo and Gasse*, 1993] indicate variability of the SW monsoon that is shorter than the Milankovitch orbital periodicities. Although any estimates of the periodicity were not reported in these communications, the present study suggests that this periodicity may be on the order of 2,200 years for the last 19,130 years. Periodicities similar to that observed here are also reported from late Pleistocene and Holocene sea-surface temperature variations in the North Atlantic [*Pisias et al.*, 1973], the Indian Ocean [*Pestiaux et al.*, 1988] and in the Camp Century ice core [*Dansgaard et al.*, 1984]·

Table 1. Radiocarbon Ages for ODP Site 723A Determined Using Accelerator Mass Spectrometer at the The Svedberg Laboratory, Uppsala University

Core	Section	Sampling Depth, cm	^{14}C Age, years BP	Error, years
1H	1	3	950	±55
1H	2	160	5,865	±65
1H	2	290	9,100	±90
1H	4	520	15,920	±125
1H	5	740	19,130	±275

Geological records and climatic simulation models have shown that Milankovitch mechanisms (solar insolation and glacial and interglacial boundary conditions) may account to some extent for long-term variations in the strength of the SW monsoon [*Prell and Kutzbach*, 1987; *Clemens et al.*, 1991., *Anderson and Prell*, 1993]. Neither solar radiations, caused by the periodic variability in the obliquity and precession of the Earth's orbit [*Clemens et al.*, 1991], nor the glacial and interglacial boundary conditions associated with the eccentricity of the Earth's orbit can explain the 2,200 years periodicity reported here. Therefore, other forcing mechanisms may account for this periodicity.

The atmospheric ^{14}C variation exhibits a periodicity of 2,300 years [*Sonett and Finney*, 1990; *Magny*, 1993] and is in phase with the $\delta^{18}O$ spectrum in the Camp Century ice core [*Dansgaard*, 1984]. Significant negative rank correlations (ranging between -0.37 and -0.47; $p<0.01$) between the planktonic foraminifer monsoon indices and $\delta^{18}O$ of planktonic foraminifera [*Niitsuma et al.*, 1989] at Site 723A, therefore, suggest a connection between the 2,200 years periodicity of the SW monsoon and the periodicity in the atmospheric ^{14}C. Further more, the trends in atmospheric ^{14}C concentrations for the last 8000 years [see figure 1 in *Damon et al.*, 1989] correspond well with the monsoon upwelling indices trend (Figure 3). Higher atmospheric ^{14}C activity has been shown to coincide with glacier expansion and lower ^{14}C activity with glacier contraction, which suggests that short-term atmospheric ^{14}C variation can serve as an empirical indicator of paleoclimatic change [*Denton and Karlen*, 1973]. Subsequent researchers also reiterate that short-term atmospheric ^{14}C variability is linked to climate [*Stuiver and Braziunas*, 1989; *Beer et al.*, 1988]. More recently, it has been emphasized that the solar modulation of the cosmic ray flux and climate-induced oceanic changes are two major contributors to atmospheric ^{14}C concentrations [*Stuiver and Braziunas*, 1993]. On the other hand, long-term ^{14}C fluctuations do not show any relationship to geomagnetic dipole moment [*Beer et al.*, 1988]. Therefore, it is possible that the long-term ^{14}C trend might be caused by a gradual increase in the speed of ocean circulation [*Lal*, 1985], which fosters vertical ocean circulation and releases ^{14}C-depleted CO_2 into the atmosphere [*Siegenthaler*, 1980]. Our reported 2,200 years periodicity of oceanic upwelling and associated monsoon could induce a 2,300 years atmospheric ^{14}C cycle through the oceanic circulation. Changes in the rate of upwelling cause a variable transport of ^{14}C-deficient waters to the surface and thus variable atmospheric ^{14}C content. Upwelling variability is related to changes in monsoon intensity (and climate), and potentially as well to atmospheric ^{14}C change. Therefore, the leading cause for both the 2,200 years monsoon and 2,300 years atmospheric ^{14}C periodicities is more likely the oceanic circulation change.

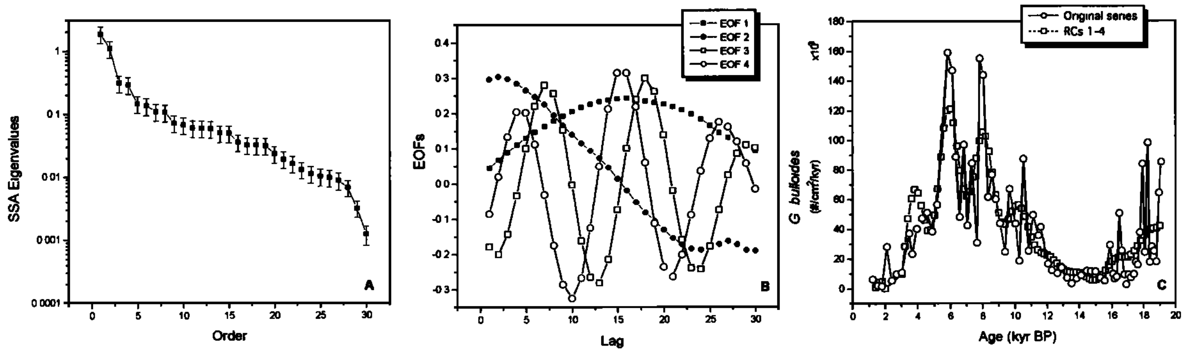

Figure 2. Singular Spectrum Analysis (SSA) of mass accumulations rates of the planktonic foraminifer species *G. bulloides* (shells >150μm), which is one of the upwelling indices used here to study late Quaternary fluctuations in the SW monsoon. (A) Eigenvalue spectrum for an embedding dimension (M) of 30; the eigenvalues are plotted on a logarithmic scale. Vertical bars represent 95% confidence intervals for the eigenvalues. Four eigenvalues stand out above the remaining eigenvalues; these four eigenvalues account for 74% of the variability in the embedding space. (B) Empirical orthogonal functions (EOFs) for the first four principal components. EOFs 1 and 2 partial out the trend in the time series, and EOFs 3 and 4 document a periodic signal of 2,200 years in the data, which is superimposed upon the general trend. EOFs 1 and 2, and 3 and 4, respectively, account for almost the same proportions of variability in embedding space (Figure 2A) and are, therefore, in phase quadrature with each other. (C) The first four reconstructed principal components (RCs 1-4), responsible for the general trend and the 2,200 years periodicity in the signal, reproduce major portions of the variability in the original series of mass accumulation rates of *G. bulloides*.

Similarly, a high resolution Late Quaternary upwelling record from the Cariaco Basin also shows coincident periodicities between the upwelling index *G. bulloides* and atmospheric ^{14}C [*Peterson et al.*, 1991]. This suggests that the long-term atmospheric ^{14}C variability might be induced by oceanic circulation and upwelling changes. Because of the link between atmospheric ^{14}C production and oceanic circulation and monsoons, it is conceivable that the thermohaline circulation of the oceans might have a bearing on the strength of the Asian monsoon system. Evidence exists that the deep-sea circulation is related to the rainfall in northern tropical areas [*Street and Perrot*, 1990].

Changes in soil moisture over high ground in south Asia and vegetation coverage [*Raman and Maliekal*, 1985], and increase in the atmospheric CO_2 and the associated increase in sea-surface temperature and evaporation will also play a part in con-

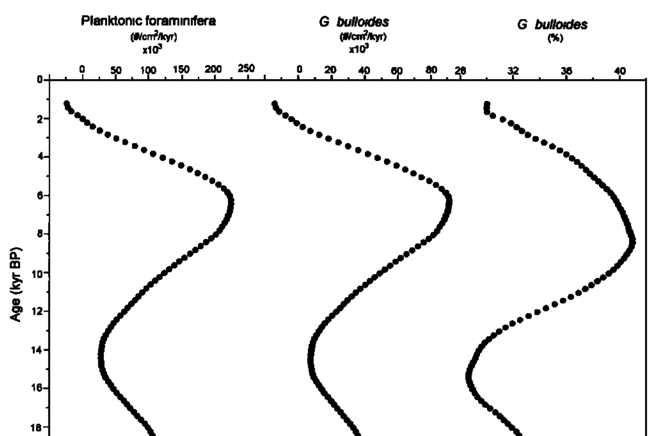

Figure 3. First two reconstructed principal components (RCs 1-2) for (A) total planktonic foraminifer mass accumulation rates, (B) mass accumulation rates of *G. bulloides* and (C) relative abundances (percentages) of *G. bulloides*. The first pair of EOFs for each data set, which is related to the general trend in the series, was used to generate these reconstructed principal components. The overall trend in all the upwelling indices is marked by greater values in the Holocene and lower values in the glacial period, indicating stronger monsoon during the Holocene and weaker monsoon during the terminal parts of the last glacial period.

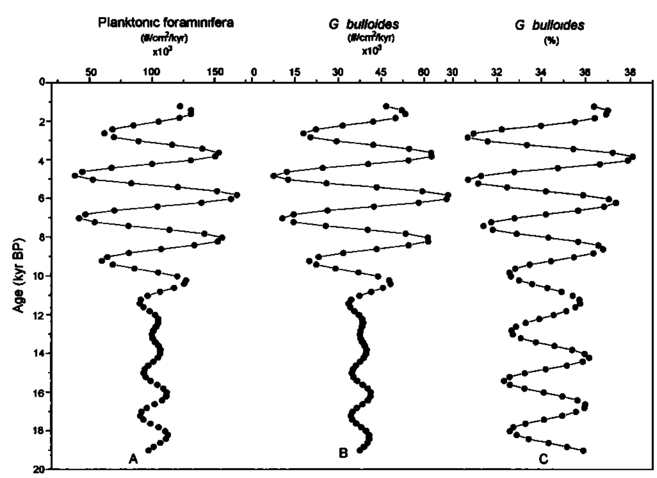

Figure 4. Reconstructed principal components 3 and 4 (RCs 3-4) for (A) total planktonic foraminifer mass accumulation rates, (B) mass accumulation rates of *G. bulloides* and (C) relative abundances (percentages) of *G. bulloides*. EOFs 3-4 were used for all series to reconstruct the portions of the variability in the series that are related to an oscillatory behaviour of the SW monsoon in the Arabian Sea with a periodicity of 2,200 years.

trolling the SW monsoon strength at decadal and century scales [*Meehl and Washington*, 1993]. All these alternatives will have various complex feedback mechanisms which modify atmospheric and oceanic circulation changes and albedo of the continental surface (especially over south Asia). This in turn changes the land-ocean heat contrast and influences the SW monsoon intensity in the eastern Africa through central Asia.

Our results suggest that oceanic circulation changes have a profound influence in driving the Asian monsoon variability and atmospheric ^{14}C concentration variations at frequencies far greater than those of Milankovitch orbital cycles.

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