

Driving Forces of Indian Summer Monsoon on Milankovitch and Sub-Milankovitch Time Scales: A Review

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Abstract: A scientific consensus exists that tectonic evolution of Himalaya is the main cause of monsoon initiation and evolution in southeast Asia. Several forcing factors such as tectonic, solar insolation, latent heat transport, albedo of the earth surface and deep water circulation changes drive the variability of southwest (SW) monsoon in the Indian subcontinent. Different forcing factors act on different time scales. Arabian Sea sediments consist of distinct fauna that are endemic to areas of upwelling. The SW monsoon wind strength, upwelling in the Arabian Sea and precipitation in the subcontinent are inter linked. Thus Arabian Sea sediments provide a record of past monsoon variability covering a time span of a few million years.

Detailed analysis of numerous monsoon indices and General Circulation Models (GCM) show that SW monsoon was strong during interglacials (warm periods) and weak during glacials (cold periods). Spectral analysis of detailed time series of monsoon indices reveal that the intensity of the SW monsoon fluctuates with periodicities of 100 ka and 23 ka. These periodicities of SW monsoon were attributed to the orbitally induced changes in solar radiation and surface boundary conditions (Milankovitch Theory). Recent high-resolution studies from the Oman Margin provide new evidences on the SW monsoon variability on century time scale and a Sub-Milankovitch Periodicity in the range of 2,200 to 2,400 years. The SW monsoon variability on century scale and high frequency periodicities might be forced by the deep water circulation changes in high latitudes. The present review discusses the atmospheric ^{14}C changes and recent onset of aridity in the tropics, which is also linked to the SW monsoon variability in one way or other.

Keywords: Milankovitch Time Scale, Monsoon, Indian Ocean.

INTRODUCTION

The summer monsoon is the dominant climatic force in tropical parts of the Indian Ocean and adjacent continents. Seasonal reversal of the wind direction between summer and winter drives the southwest (SW) and northeast (NE) monsoons in the Indian Ocean and rainfall in Asia. The fundamental mechanisms of the monsoon are 1) the differential heating of land and ocean and the resulting pressure gradient that drives the winds from high-pressure to low-pressure zones, 2) the swirl introduced to the winds by the rotation of the earth, and 3) moist processes that determine the strength, vigour, and location of the major monsoon rainfall.

During the northern hemisphere summer high solar radiation causes intense sensible and latent heating over central Asia, especially over northern India and Tibet Plateau. The pattern of heating causes an ascending air flow to the

atmosphere, which leads to the development of an intense low-pressure cell that is centered over Asia. At the same time, a high pressure cell develops over the southern Indian Ocean due to the southern hemisphere winter and the greater specific heat of the water. Thus an atmospheric pressure gradient between the Asian continent and the cooler southern Indian Ocean induces a large-scale meridional overturning, with the lower circulation limb being the strong low-level SW summer monsoon winds of the western Indian Ocean (Fig. 1). These marine air masses converge over the Indian subcontinent and are uplifted due to heating and orographic steering, which causes seasonal monsoon rains (Hasternath, 1985; Webster, 1987). During the winter the Asian sector is characterized by low solar radiation, low temperatures, and NE winds, which flow from the cold Asian continent towards the Arabian Sea. These continental winter monsoon

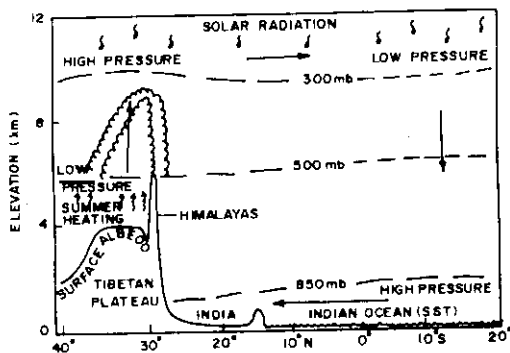


Fig. 1. Schematic diagram of the Indian ocean monsoon geometry and processes. Summer season causes sensible heating of the Tibet Plateau and subsequent latent heating of the atmosphere above the southern Asia (From Prell et al. 1992).

winds are characterized by relatively low velocity and, therefore, carry little moisture (Hasternath and Lamb, 1979).

ECONOMIC IMPACTS OF THE MONSOON

Most of the less developed countries are situated within the tropical and monsoon influenced regions of the world. Agricultural production in these countries is critically influenced by weather, and these countries are predominantly dependent upon agriculture; their overall performance is highly sensitive to weather uncertainties. In the absence of monsoons that bring adequate rain, life styles can be seriously and occasionally irreversibly disrupted. The first effect of insufficient rains is crop yield reduction or crop death. In addition, recurrent drought may cause a serious shortage of drinking water for humans and animals. Water reservoir levels drop, reducing the generation of hydroelectric power, and the resulting energy shortages limit agricultural and industrial production. The unique monsoon circulation in the Indian Ocean and associated rainfall over Asia thus have a fundamental impact on the socio-economic and agricultural development in the densely populated Asian countries.

OCEANOGRAPHIC SETTING

The surface oceanography of the northern Indian Ocean is driven by a seasonally changing

monsoon gyre, which is not found in any other ocean. This monsoon gyre is separated from the southern subtropical gyre by a very pronounced front in the hydro-chemical structure at about 10°S , a unique feature of the Indian Ocean (Wyrtki, 1973). The monsoon wind system of the Indian Ocean causes a striking semiannual reversal of the surface currents in the Arabian Sea and the Bay of Bengal (Wyrtki, 1973). During the SW monsoon (May through October) the surface low level of southeasterly trade winds of the Southern Hemisphere extend across the equator to become southerly or southwesterly in the Northern Hemisphere. The frictional stresses of these southwesterly winds in turn drive the Somali Current (SC) flowing northward as a western boundary current, the westward flowing South Equatorial Current (SEC), and the eastward flowing Monsoon Current (MC) (Fig. 2). The northward flowing Somali Current invokes intense upwelling along the coast of

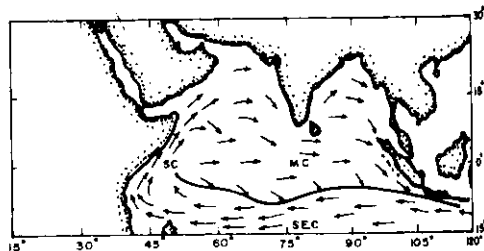


Fig. 2. Surface circulation in the Indian Ocean during the SW monsoon (From Wyrtki, 1971).

Somalia (Bruce, 1974; Schott, 1983). The Somali Current turns to the east at 11°N ; the upwelling is terminated by the flow of warm surface water from the Gulf of Aden, which forms a strong temperature front (Wyrtki, 1973). This warm surface water, coming from the Gulf of Aden and flowing into the central Arabian Sea, separates the upwelling along the coast of Somalia from that along the coast of Arabia.

During the SW monsoon period the strong winds blow parallel to the Oman coast and develop another center of intense upwelling, but here no strong currents develop parallel to the coast (Wyrtki, 1973; Bruce, 1974; Elliot and Savidge, 1990; Bauer et al. 1991). The volume

and nutrient enrichment caused by the upwelling along the Oman Margin is stronger compared to the volume and nutrient enrichment resulting from upwelling along the Somalia Margin (Wyrski, 1973; Bruce, 1974; Shallow, 1984). Previously, two separate mechanisms were suggested for the SW monsoon upwelling off Arabia: (1) coastal upwelling due to Ekman divergence of surface water offshore under the influence of strong winds parallel to the coast, and (2) open-sea upwelling further offshore driven by the strong positive wind stress curl to the northwest of the axis of the Somali Jet (Smith and Bottero, 1977; Shallow et al. 1984; Brock et al. 1992). Both coastal and open-ocean upwelling processes increase the nutrient concentration in the surface water and foster high biological productivity in the Arabian Sea (Wyrski, 1973; Qasim, 1982). Along the west coast of India weak upwelling centres develop during this period (Wyrski, 1973).

Oceanic circulation during the NE monsoon is relatively weak and characterized by the North Equatorial Current (NEC), an eastward flowing Equatorial Counter Current (ECC), and a moderately developed anticyclonic gyre (Fig.3). During the NE monsoon sporadic upwelling occurs in the northeastern Arabian Sea (Wyrski, 1973).

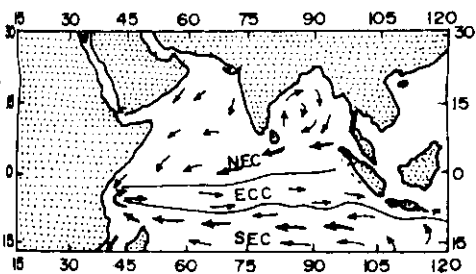


Fig.3. Surface circulation in the Indian Ocean during NE monsoon (from Wyrski, 1971).

Two surface-water masses form in the northern Indian Ocean (Wyrski, 1973). A high-salinity water mass is formed in the Arabian Sea due to excess evaporation and the subsurface flow of Persian Gulf and Red Sea water. A low-salinity water mass is formed in the Bay of Bengal by excess precipitation and abundant river runoff. Thus a great salinity gradient exists

in the northern Indian Ocean. The low-salinity water mass of the Bay of Bengal flows to the south of Ceylon; one branch continues westward along a latitude of 5°N and another branch extends northwesterly along the coast of India during the NE monsoon.

In contrast to the salinity pattern in the northern Indian Ocean, variation in sea-surface temperature (SST) is minor. Much of the regional temperature variation is due to upwelling of cooler subsurface waters in the western Arabian Sea during the SW monsoon. This creates an east-west temperature gradient in the region (Fig. 4). During the NE monsoon,

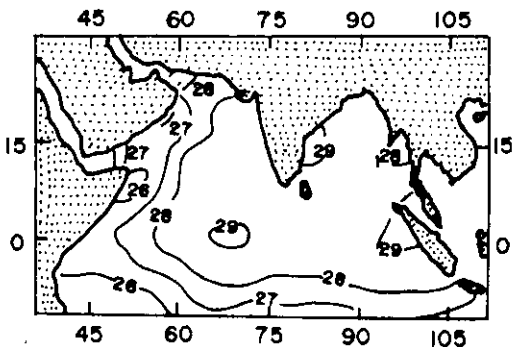


Fig.4. Average sea surface temperatures in the northern Indian Ocean during the SW monsoon (from Cullen and Prell, 1984).

equatorial surface waters remain between 28°C and 28.5°C. A weak north-south temperature gradient is observed in the Bay of Bengal, and a weak NW-SE gradient occurs in the Arabian Sea (Fig. 5).

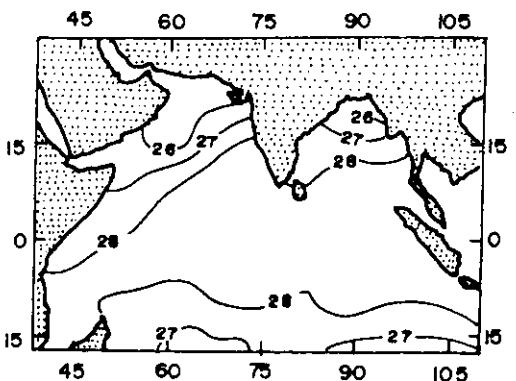


Fig.5. Average sea surface temperatures in the northern Indian ocean during the NE monsoon (from Cullen and Prell, 1984).

In the entire Arabian Sea the intermediate waters are characterized by low oxygen concentrations (Wyrki, 1971). The combined effects of (i) the high productivity and associated higher input of organic matter and parts of its subsequent oxidation within and below the thermocline, (ii) the sluggish intermediate water circulation, and (iii) the strong tropical-subtropical thermocline prevent downward mixing of oxygenated surface water and cause the development of an intense oxygen minimum zone (OMZ), between depths of about 150 and 1000 m (Spencer et al. 1982, Qasim, 1982). Although the OMZ is not directly influenced by the monsoon winds and precipitation, the monsoon driven upwelling and productivity patterns and regional precipitation/evaporation balance are factors that partially determine the extent and intensity of the OMZ.

LINK BETWEEN MONSOON, UPWELLING, AND SEDIMENT RECORD

As mentioned above, the SW monsoon winds drive the intense upwelling off Oman and Somalia and sporadic upwelling along the

southwestern coast of India. The strength of the SW monsoon winds, upwelling in the Arabian Sea, and precipitation in south Asia are strongly tied together. These upwelling waters are characterized by cool SSTs and enriched phytoplankton biomass. Distinctive planktonic fauna and flora thrive in these upwelling waters. Northeasterly winds during the winter suppress the upwelling and lower the productivity in the western Arabian Sea. Thus the southwesterly and northeasterly winds produce a striking seasonal contrast in primary productivity in the western Arabian Sea (Kobanova, 1968). Sediment-trap data from the western Arabian Sea show that not only biogenic fluxes are linked to the SW monsoon, but also lithogenic fluxes are much higher during the SW monsoon period (Nair et al. 1989; Haake et al. 1993 (Fig.6). These studies show that more than 70% of the calcareous, siliceous, and lithogenic material is supplied to the Arabian Sea during the SW monsoon period. In other words, the SW monsoon accounts for about 70 to 80% of the total annual productivity. These seasonally dominant particles eventually settle onto the seafloor to

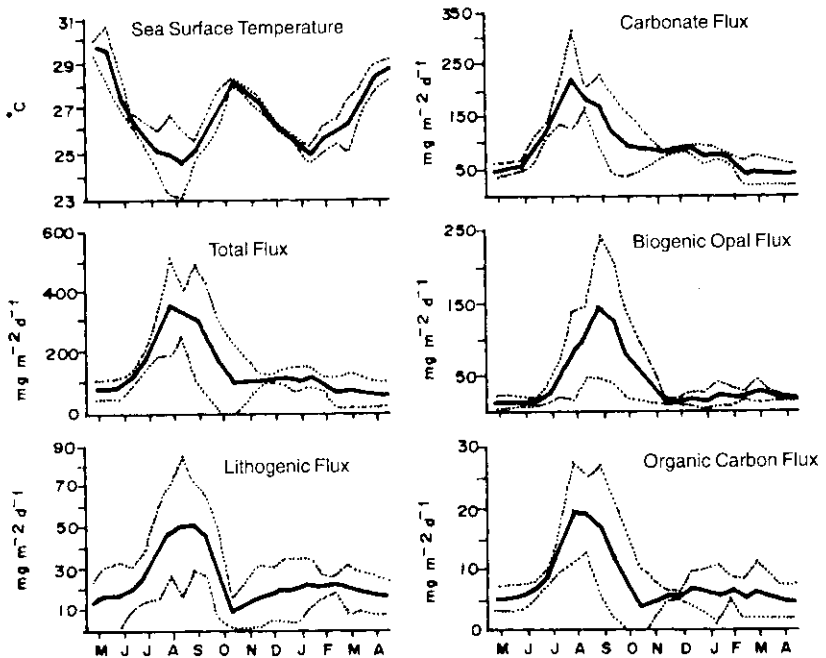


Fig.6. Sea-surface temperature, total, biogenic, lithogenic, carbonate, opal, and organic carbon flux for the whole period of sediment-trap observations at the western trap site (from Haake et al. 1993).

form a distinct biogeochemical record of upwelling (Prell and Curry, 1981; Naidu, 1990; Naidu et al. 1992). The upwelling, and associated productivity events are largely driven by Ekman transport; their duration and intensity reflect the structure and strength of the monsoonal winds.

Understanding the evolution and variability of the Indian Ocean summer monsoon was the primary goal of Ocean Drilling Program Leg. 117 (Prell and Niitsuma, 1989). Here, I summarise some of the records of monsoon-related variability that have resulted from the study of ODP Sites 722B and 723A. ODP Site 722 and RC-27-62 were located on the Owen Ridge (Fig. 7). Following the uplift of the ridge during late Oligocene to early Miocene time, the ODP Site 722 and RC-27-62 have been above the reach of turbidite deposition associated with the Indus Fan and has accumulated primary pelagic, carbonate-rich sediments. Site 723 was located in the centre of the mid-slope basin of the Oman Margin at a water depth of 807.8 m. Here the rate of

sedimentation varies from 31 to 69 cm/ka, this site therefore, provides high-resolution record of upwelling history from the last glacial to Holocene.

MONSOON VARIABILITY ON MILANKOVITCH ORBITAL TIME SCALE

Detailed records of monsoon variability for the past 350 ka are available from the ODP Sites 722B and 723A. Analyses of the various monsoon tracers such as *G. bulloides*, barium flux, opal flux and lithogenic grain-size records reveal that the SW monsoon is intense during interglacial periods and weak during glacial periods (Clemens et al. 1991) (Figs.8 and 9). The minor differences in the exact timing and relative amplitude of such events in different monsoon tracers can be attributed to mechanism not directly related to monsoon variation. For example, the accumulation of bulk lithogenic material is closely linked to changes associated with continental glaciation and reflect variations in source area aridity and

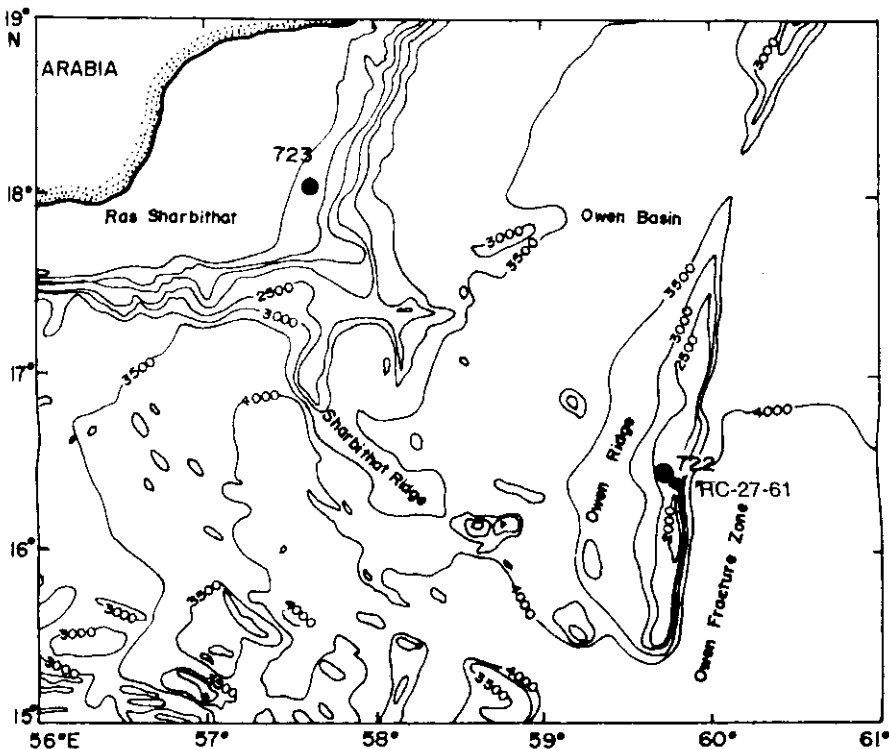


Fig.7. Location of ODP Sites 722, 723 and RC 27-61, physiography and bathymetry of the western Arabian Sea.

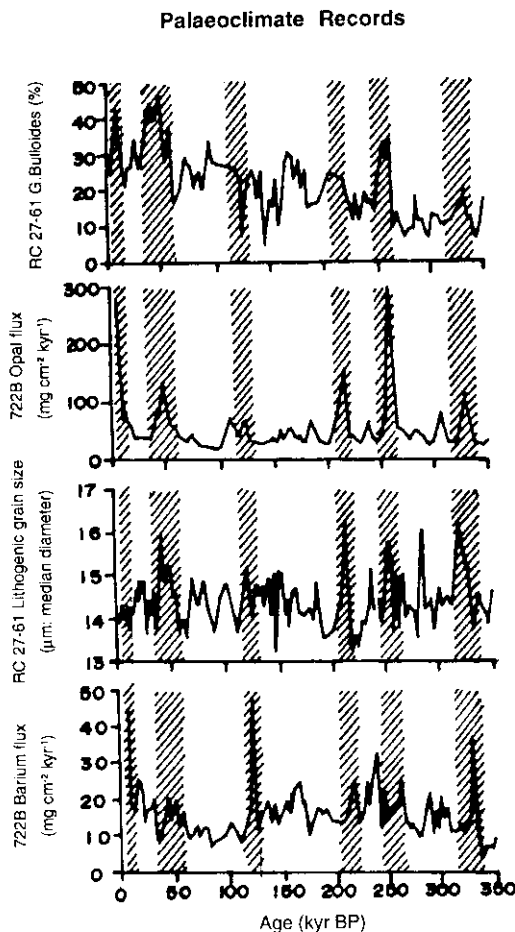


Fig.8. Records of monsoon upwelling indices preserved in the Arabian sea sediments. A. Percentage of *G. bullioides*, B. Opal flux, C. Lithogenic grain size and D. Barium flux (from Clemens et al. 1991).

exposure rather than monsoon intensity. Spectral analyses of time series monsoon tracers data generated from the ODP Site 722 has documented periodicities at 100 ka, 41 ka and 23 ka (Fig. 10). The orbital periodicities occur in every site and in number of biological, chemical, and sedimentological records in the western Arabian Sea (Prell et al. 1992).

The cross spectral analyses between the orbital parameters and monsoon tracers demonstrate varying degree of coherence. Strong coherencies are recorded over the precession band, moderately strong coherencies are recorded over the obliquity band, and

moderate to weak coherencies are recorded over the eccentricity band. *G. bullioides* and grain-size show negligible coherence with eccentricity (Fig. 10 a and b), whereas opal and barium show significant coherence (Fig. 10 c and d).

The relative influences of external and internal forcing mechanisms on monsoon variability can be estimated by using coherence and phase relationships between individual monsoon tracers and each internal forcing mechanism. The precessional phase wheel shows strong coherence between all four monsoon tracers and variance associated with precessional radiation at 80% confidence interval (Fig. 11a). However, maxima in monsoon response lags about 8 ka with the maxima in precessional insolation forcing. Similarly maxima of monsoon strength lags about 2.5 ka with ice-volume minima and with minimum cold-season SSTs in the southern subtropical Indian Ocean. Modelling experiments (Kutzbach and Guetter, 1986; Prell and Kutzbach, 1987) have shown that the summer radiation pattern associated with increased precession of the Earth's axis induces strong monsoon. The phase differences between monsoon tracers and insolation changes in the northern hemisphere reveals that the insolation changes associated with the precessional changes of Earth's axis is not solely responsible in causing the strong monsoons.

The obliquity phase wheel shows that strong monsoons occur simultaneously with maxima in northern hemisphere radiation and minima in the southern subtropical SST (Fig. 11b). The near zero phase relationship between southern subtropical SST minima and maxima in the monsoon strength indicate that latent heating may also play a part in setting the phase of strong monsoons over obliquity bands (Clemens et al. 1991).

The eccentricity phase wheel shows that the subtropical SST minima significantly lead maxima in Arabian Sea monsoon strength (Fig. 11c). Therefore small amount of variance concentrated at the 100 ka can not be accounted for by environmental conditions associated with global ice-volume fluctuations, nor by the availability of latent heat (Clemens et al. 1991).

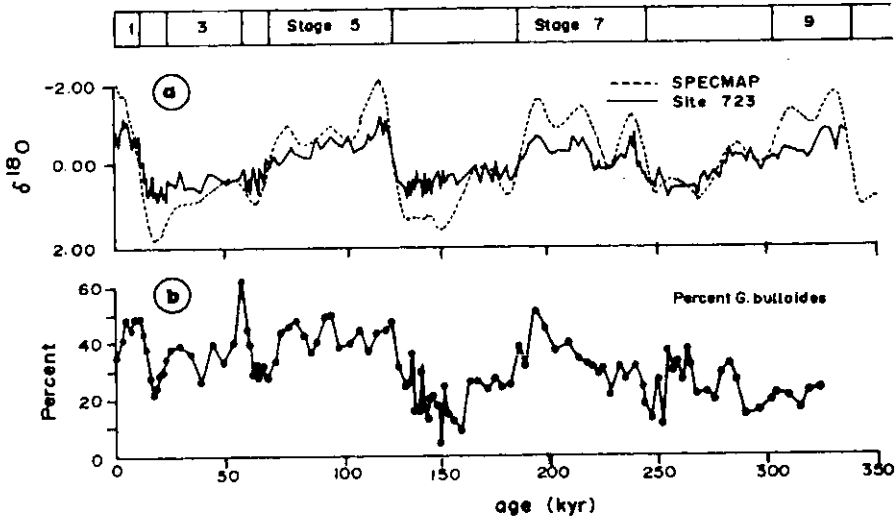


Fig.9. Oxygen isotope time series for Site 723B superimposed on the SPECMAP composite oxygen isotope time series and relative abundance of *G. bulloides* (from Prell and Anderson, 1993).

DIFFERENCES BETWEEN OMAN MARGIN AND OWEN RIDGE SITES

Over the interval spanning the last 350 ka there are some events such as peaks in *G. bulloides* abundance at 9 ka and 60 ka, were documented in both Oman Margin and Owen Ridge regions. However, some differences exist particularly the absence of the glacial-interglacial pattern at the offshore sites. In the frequency domain the offshore time series lacks the large concentration variance at 100 ka and 23 ka observed in Site 723B (Fig. 12). Instead, there is a broad maximum in variance around 50 ka and a small peak variance at 23 ka. The most likely explanation for the regional differences in the *G. bulloides* time series are differences in the physical upwelling processes that effect these sites.

Anderson and Prell (1992) reasoned out that in the coastal region (Oman Margin) upwelling is directly related to the Ekman transport offshore, and is thus linearly proportional to the along shore wind stress. Farther offshore (Owen Ridge), open-ocean upwelling is driven by the positive curl in the wind stress. In historical records little correlation exists between stronger winds and increased open-ocean upwelling. In the offshore region where the sediment cores were

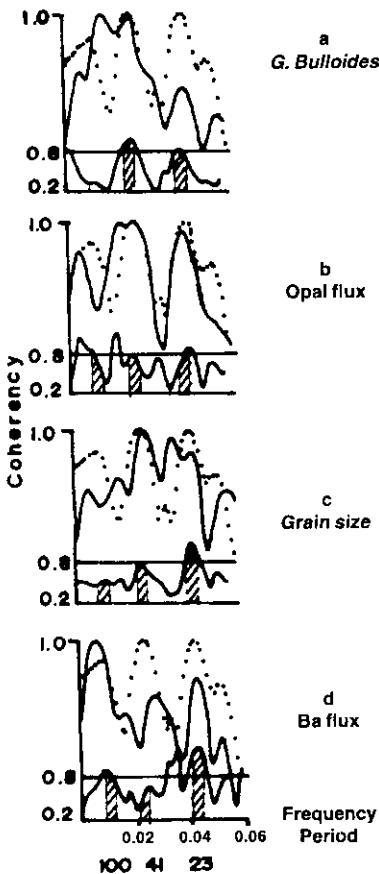


Fig.10. Cross spectra of ETP with (a) *G. bulloides*, (b) opal flux, (c) grain size and (d) barium flux (from Clemens et al. 1991).

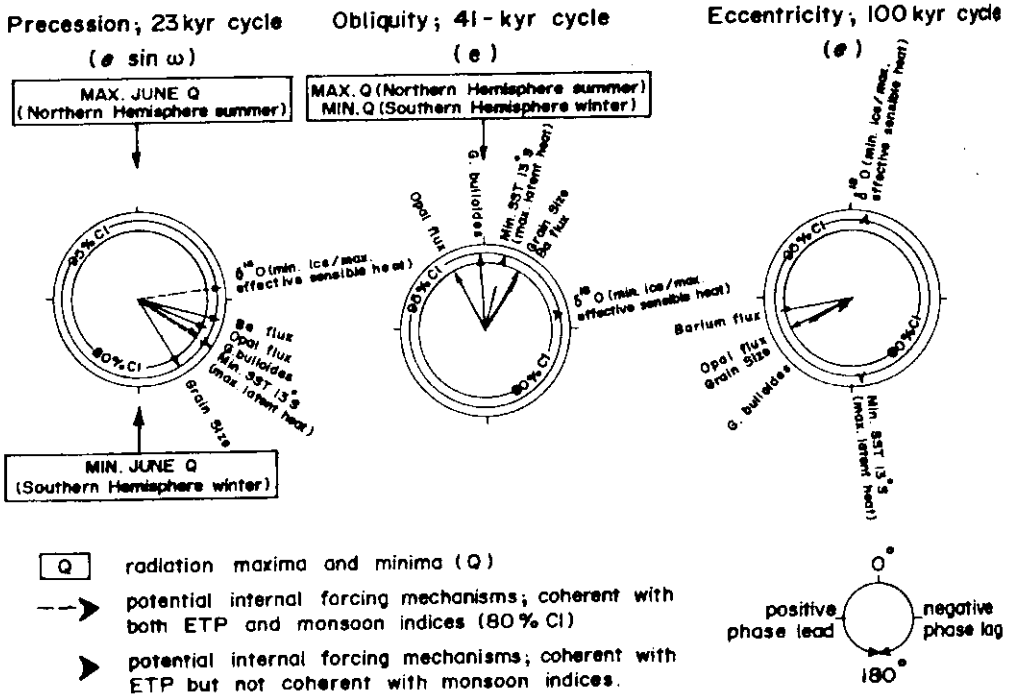


Fig.11. Coherence and phase summary. The purpose of the phase wheel diagram is to display all the available cross spectral relationships between orbital variations and changes in monsoon climate tracers. Zero phase on each wheel is set at (a) maximum precession, (b) maximum obliquity and (c) maximum eccentricity (from Clemens et al. 1991).

recovered, the year with strongest winds was accompanied by weaker wind stress and diminished upwelling (indicated by warm sea surface temperatures and decreased

phytoplankton pigment content) because the region of maximum wind stress curl moved NW that year. Therefore, the offshore sites are not suitable in tracing the monsoon-induced upwelling in the Arabian Sea.

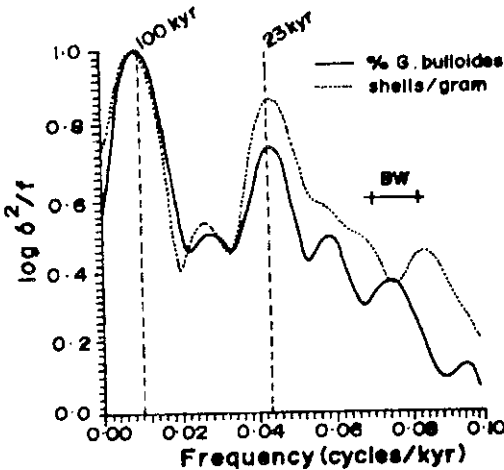


Fig.12. Scaled log variance density of *G. bulloides* and shell concentration as a function of frequency. Periods of 100 ka and 23 ka are labeled (from Anderson and Prell, 1993).

MONSOON VARIABILITY ON CENTURY TIME SCALE

The three indices of upwelling based on planktonic foraminifera used here, namely fluxes of total planktonic foraminifera and *G. bulloides*, and relative abundance of *G. bulloides*, are hereafter referred to as upwelling indices. The relative abundance of *G. bulloides* may not exactly mirror the fluxes of total planktonic foraminifera and *G. bulloides*, because the relative abundance of *G. bulloides* depends on productivity changes in the other planktonic foraminifer species. However, all three upwelling indices show significant rank correlations with each other through time. The changes in these upwelling

indices are interpreted in terms of variability in the SW monsoon strength.

From 19 to 15.9 ka both relatively high and low values of the upwelling indices are recorded, indicating that the strength of the SW monsoon was alternatively between strong and weak (Fig. 13). During the latest parts of the Pleistocene, from 15.8 to 12 ka, the lowest values of the upwelling indices noted here indicate that the weakest SW monsoon occurred within this interval. Water levels in African lakes are also at minimum between 15 and 12 ka compared to levels during the last glacial maximum (LGM) at 18 ka (Street and Grove, 1979), suggesting that the SW monsoon was weakest after the LGM. Earlier, it has been suggested that the SW monsoon was weak during the LGM, because of the greater albedo due to extensive ice sheets in the northern hemisphere and lesser solar radiation at this time (Prell, 1984; Prell and Kutzbach, 1987). In contrast, high-resolution monsoon upwelling record shows that the SW monsoon was

moderately stronger during the LGM and weaker between 15.9 and 12 ka (Naidu and Malmgren, 1996). Numerous studies point to a maximum thickness of ice sheets at about 18 ka in the northern hemisphere (CLIMAP, 1976) when solar insolation was at its minimum (Berger, 1978). High resolution monsoon upwelling data suggest that the SW monsoon was reduced in strength to a minimum after the LGM, indicating that the intensity of the SW monsoon is not linearly related to the ice sheet thickness and solar radiation changes in the northern hemisphere during the LGM (Naidu and Malmgren, 1996).

Increases in the upwelling indices at 12 ka indicate the initiation of SW monsoon winds (Fig. 13). This increase in upwelling coincides with the maximum rate of glacial melt-water discharge in the northern hemisphere (Fairbanks, 1989) and increase in summer insolation (Berger, 1978). Maximum values of the upwelling indices from 10 to 5 ka reflect the most intense upwelling and strongest SW

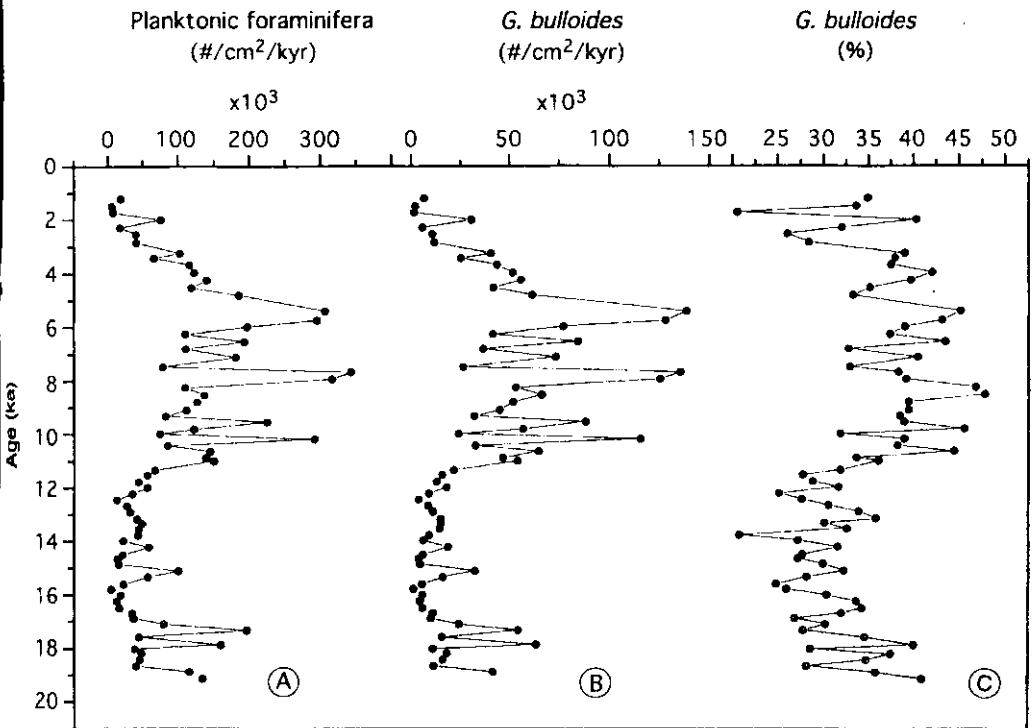


Fig.13. High resolution record of fluxes of total planktonic foraminifera and *G. bulloides* and percentages of *G. bulloides* at ODP Site 723A (from Naidu and Malmgren, 1995).

monsoon in the western Arabian Sea during the time interval covered by Naidu and Malmgren (1995). This period coincides with higher water level in lakes from Africa, Arabia, and India (Street and Grove, 1979). Although the present record demonstrates that the SW monsoon strength was greatest during 10 to 5 ka, a few intervals during this period are marked by low values of the upwelling indices, reflecting brief periods of a weaker SW monsoon. On the other hand, these values are higher than the minimum values noticed in the interval <15 to 12 ka and after 5 ka, which suggests that the SW monsoon was generally stronger during 10 - 5 ka.

The values of the upwelling indices started to decrease at 5 ka, which reflects a weakening of the SW monsoon. The lowest upwelling indices in the Holocene are recorded between 3.5 and 1 ka, which suggest that upwelling decreased and the SW monsoon became weaker during this period. This inference is corroborated by water levels in Ethiopian lakes (Gillespie et al. 1983), paleohydrological data from western Tibet (Gasse and Van Campo, 1994) and pollen records from northwest India (Singh et al. 1974) and eastern Arabian Sea (Caratini et al. 1994). It is thus clearly evident that an arid phase of the climate began at 3.5 ka in the Asian tropics.

An obvious, but provocative question is whether the onset of arid climate at 3.5 ka is traceable in other tropical regions of the world? Evidences such as $^{18}\text{O}/^{16}\text{O}$ ratios in ostracod shells from Caribbean lakes (Hodell et al. 1991) and pollen analysis from south Australian lake (Singh and Luly, 1991) have also documented the onset of an arid phase at 3.5 ka. Thus, the onset of arid climate at 3.5 ka appears to be a global event, prevailing throughout the late Holocene.

Coherent occurrence of an arid climate at 3.5 ka in the northern hemisphere (Hodell et al. 1991, Gasse and Van Campo., 1994 and Naidu, 1996) and in southern hemisphere (Singh and Luly, 1991) suggests that late Holocene climate changes of the tropics in both hemispheres were in phase.

Several forcing mechanisms, such as solar radiation and albedo changes (Prell, 1984),

glacial and interglacial boundary conditions, orbitally produced changes in solar radiation (Prell and Kutzbach, 1987), externally forced by cyclic changes in solar radiation and internally phase-locked to the transport of latent heat from southern subtropical Indian Ocean to the Tibetan Plateau (Clemens et al. 1991), have been suggested to explain the SW monsoon variability on time scales of 10^3 to 10^5 . All these forcing mechanisms are linked to the orbital periodicities in one way or other. The question is whether these mechanisms work on a sub-Milankovitch time scale. In this study, we test the latent heat transport mechanisms introduced by Clemens et al. (1991) on our high-resolution data.

The upwelling indices used here (Fig. 13) are compared to the solar insolation data for the latitudes of 30°S and 30°N (Fig. 2 in Naidu and Malmgren, 1996). We have chosen to use the solar insolation data for the month of May for 30°S , because, the onset of the SW monsoon takes place in May. Greater solar insolation during this month leads to higher sea-surface temperatures (SST), which causes lower latent heat supply to the troposphere. The insolation data for a 30°N latitude for the summer (June, July and August) provide the air pressure information (greater insolation means low pressure and vice versa) in the Asian Continent. The comparison of changes in upwelling indices with the insolation curves for the latitudes of 30°S and 30°N indicate that the insolation changes account for the general pattern of variability in monsoon activity, but it does not explain the short-term changes for the last 19 ka.

Therefore, some other mechanisms must be involved in the forcing of the observed short-term changes. The albedo changes in the high grounds of Asia might be one of the important agents in driving the short-term abrupt variability in the SW monsoon system. The albedo changes may be caused by waning and waxing of low-latitude glaciers in the Tibet Plateau (Zahn, 1994) and changes in soil moisture and vegetation coverage (Raman et al. 1985). There are no geological data documenting the history of albedo changes on

the Plateau. In addition to the albedo changes cross-equatorial heat transport by thermohaline circulation of the ocean and associated changes in atmospheric ^{14}C concentrations might have contributed to the short-term SW monsoon changes.

SUB-MILANKOVITCH PERIODICITY IN THE MONSOON SYSTEM

In addition to the variability of SW monsoon induced upwelling strength the single spectrum analysis (SSA) of the mass accumulation rates of *G. bulloides* from the ODP Site 723A indicates that the first four eigen values λ_1 - λ_4 stand out above the remaining eigen values and are interpreted as significant (Fig. 14A). These eigen values account for 74% of the variance in the embedding space. The occurrence of pairs of eigen values 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 eigen values (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 (Naidu and Malmgren, 1995) (Fig. 14B). 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 (Fig. 14C). SSA of the relative abundances of *G. bulloides* and total mass accumulation rates of planktonic foraminifera exhibit similar results.

The 2,200 years periodicity exhibited by EOFs 3 and 4 is superimposed upon the major trend in the data for mass accumulation rates of total planktonic foraminifera (Fig. 15A) and mass accumulation rates of *G. bulloides* (Fig. 15B). RCs 3 and 4 of percentage of *G. bulloides* give evidence for a periodicity of 2,400 years (Fig. 15C). If the fluctuations in these variables are a result of the same forcing

mechanism, this therefore points to the oscillatory behaviour of the summer monsoon climate with a periodicity range of 2,200 - 2,400 years. High resolution Multi Taper Method (MTM) spectral analysis confirms the existence of a periodicity in this range. We believe that mass accumulation rate is the best indicator of upwelling, because mass accumulation rates are not influenced by the productivity changes of other species and it also takes into consideration the effect of dilution caused by variation in sedimentation rates.

The amplitude of the SW monsoon variations is much higher during the Holocene than during the last glacial period (Fig. 15). Several other sets of data, like tropical lake levels (Street and Grove, 1979) 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 in the range 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).

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

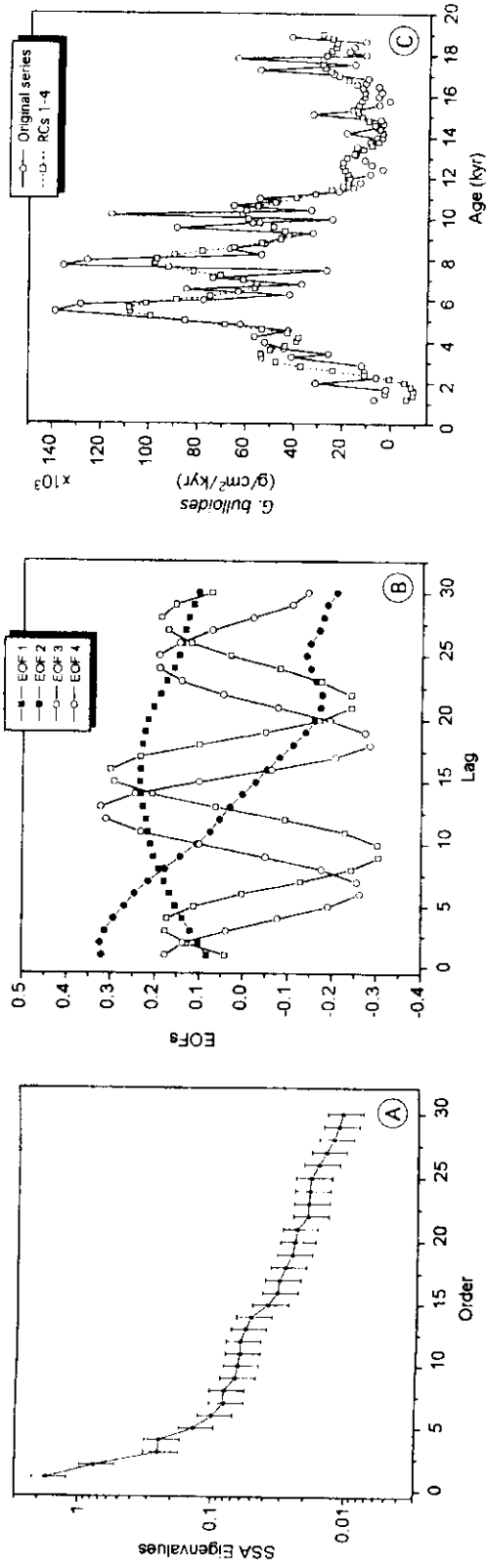


Fig.14. Singular Spectrum Analysis (SSA) of mass accumulation rates of the planktonic foraminifer species *G. bulloides* (shells >150µm), which is one of the upwelling indices used to study late Quaternary fluctuations in the SW monsoon. (A) Eigenvalue spectrum for an embedding dimension (M) of 30; the 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* (from Naidu and Malmgren, 1995).

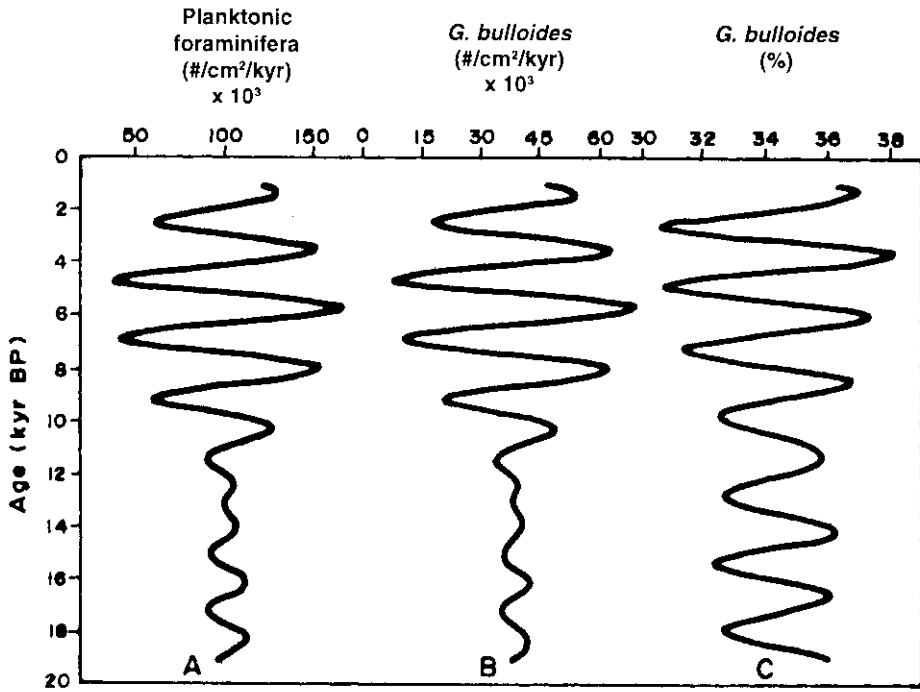


Fig.15. Reconstructed principal components 3 and 4 (RCs 3-4) for (A) total planktonic foraminifer mass accumulation rates, (B) mass accumulation rates of *G. bulloides* show a periodicity of 2,200 years, and (C) relative abundances (percentages) of *G. bulloides* show a periodicity of 2,400 years. EOFs 3-4 were used for all series to reconstruct the portions of the variability in the series that are related to an oscillatory behavior of the SW monsoon in the Arabian Sea with a periodicity range of 2,200 - 2,400 years (from Naidu and Malmgren, 1995).

$\delta^{18}O$ spectrum in the Camp Century Ice Core (Dansgaard et al. 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 (Fig. 13). 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 (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 upwelling variability

may result in ^{14}C changes. Therefore, the leading cause for both the 2,200 years monsoon and 2,300 years atmospheric ^{14}C periodicities is the oceanic circulation change.

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 controlling 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 eastern Africa through central Asia.

SUMMARY

The summer monsoon is a strong local to regional climate response that is superimposed on other regional and global trends in climate and ocean circulation and chemistry. The primary challenge in understanding the history of the monsoon system is to unravel its influence on the oceanography and sediments from other synchronous processes that are not directly related to the monsoon system. The western Arabian Sea is one of the areas where we can isolate the effect of summer monsoons by means of upwelling process. The SW monsoon winds

drive the intense upwelling off Oman and Somalia and sporadic upwelling along the southwest coast of India. The strength of SW monsoon winds, upwelling in the Arabian sea, and precipitation in southeast Asia are strongly coupled together. The upwelling results in a distinctive planktonic faunas and floras which settles on the sea bottom and forms a geological record of upwelling. By studying the biogeochemical parameters of these sediments we are able to tell the history of summer monsoon evolution and variability in the geological past. Some of the important findings from the ODP Sites 722 and 723 are:

1. The monsoon indices data such as *G. bulloides*, Barium flux and lithogenic content show high values during interglacials and low values during glacials which reflects that the summer monsoons are intense during glacials and weak during interglacials.
2. Spectral analyses of detailed time series of many sedimentary components from both Oman Margin and Owen Ridge sites have documented that the sedimentary record contains pervasive variability at the orbital scale over wide range of time scales during Quaternary. Much of this variability is coherent with either orbital variations (eccentricity, obliquity, or precession) or with glacial and interglacial changes as recorded by $\delta^{18}\text{O}$. The spectral peaks differ in their distribution of variance according to the time interval analyzed, the location of site and the type of sediment component analyzed. Analyses of the various indicators of the monsoonal upwelling have shown that the sedimentary record of the monsoon related to orbital forcing is complex. However, the relationship between different indicators can be used to constrain the interpretation of past monsoonal variation.
3. Monsoon upwelling indices between the Oman Margin and Owen Ridge document difference in spectral peaks and variance. Oman Margin record show greater variance at 100 ka and 23 ka, whereas the Owen Ridge Site exhibits greater variance at 41 ka and 23 ka. Different processes are operating at the coastal and offshore regions which explains the observed changes between the Oman Margin and Owen Ridge sites. Upwelling occurs at Oman Margin due to the offshore Ekman transport, and is linearly proportional to the along shore wind stress. Farther offshore, open-ocean upwelling is driven by the positive curl in the wind stress.
4. The high resolution record from the Oman Margin (ODP Site 723B) provides new evidences on the summer monsoon variability at century time scales and the century scale variability can not be solely explained by the orbital forcing factors such as

Eccentricity, Obliquity and Precession. Instead the short term monsoon variability can be explained by the deep water circulation changes in the high latitudes.

5. The upwelling indicators (Fluxes of *G. bulloides* and total planktonic foraminifera and percentages of *G. bulloides*) document a 2,200 years cyclicity. High resolution monsoon upwelling studies 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.

6. The decreasing upwelling indicator values in the late Holocene from 3.5 ka reflects a weakening phase of summer monsoon. This and other paleohydrological data from Tibet, China and Australia record an arid climate around 3.5 ka.

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