

Wind Strength Variability in the Western Arabian Sea since the Last Glacial Maximum: Southwest vs. Northeast Monsoon Modes

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Abstract: Both the southwest monsoon (SWM) and the northeast monsoon (NEM) winds are responsible for the variations in the biological productivity in the western Arabian Sea (WAS), as recorded in the Arabian Sea sedimentary planktic foraminiferal record. While most earlier studies from this region ascribe the total observed variability predominantly to SWM, here we attempt to differentiate between the two monsoons based on the relative abundances of depth stratified planktic foraminifera assemblages. We observe a number of intervals of enhanced SWM. The first intensification (SWMI-I) occurred during ~16 to 12 ka and is possibly an outcome of early deglacial melting and stepwise increase in SWM strength after the end of the last glacial maximum (LGM). The second intensification (SWMI-II) is recorded at around ~10 ka, after the gradual strengthening from the end of the Younger Dryas cold episode. The last interval of intensification (SWMI-III) occurred around (~8.2 to 7.8 ka). In addition, there are two intervals of enhanced NEM: NEMI-I at around 19 to 17 ka and NEMI-II (~8.0 to 5.4 ka). These intervals of two enhanced NEM and three SWM wind strengths are bridged by decline in the SWM at different intervals, such as SWMD-I (~17 to 16 ka), SWMD-II (~12 to 11 ka) and SWMD-III (9.7 ka to 8.2 ka).

Keywords: Southwest monsoon, Northeast monsoon, Planktic foraminifera, Holocene, Last Glacial Maximum.

Introduction

Understanding the timing of the past variability of monsoon intensities is vital for the prediction of monsoon (Gadgil et al., 2006). Towards this end, attempts have been made by studying planktonic foraminiferal and oxygen isotope records in the sediments of the Arabian Sea over the past decade. The period spanning the Last Glacial Maximum (LGM) to the present offers a unique opportunity to study monsoon variability in the deglacial background with short perturbations of cold

events such as the Younger Dryas and Bond events (which also includes the 8.2 ka cooling event, related to the Bond event 5). Besides the fluctuations in the position of the inter-tropical convergence zone (ITCZ), interesting correlations have been demonstrated through various paleomonsoon proxies between the monsoon wind strength and insolation (Overpeck et al., 1996; Sirocco et al., 1999; Sirocco et al., 1999; Webster et al., 1998; Gupta et al., 2005; Tiwari et al., 2005a), El Niño-Southern Oscillation (Overpeck et al., 1996; Schulz et al., 1998; Sinha et al., 2006), Indian Ocean Dipole (Saji

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et al., 1999; Webster et al., 1999; Ashok et al., 2001) and rapid change in north Atlantic climates (Gupta et al., 2003; Gupta et al., 2005; Hong et al., 2003). Several studies showed that the physical mechanism through which the North Atlantic climatic perturbations and monsoon are linked is unclear (as detailed by Gupta et al., 2005). Some studies infer that both are related to insolation changes and thus a correlation is observed (Agnihotri et al., 2002; Gupta et al., 2005; Wang et al., 2005), while others link the variation in monsoon and north Atlantic climate to abrupt reorganizations of the ocean thermohaline circulation, leading to redistribution of energy, changing temperature and moisture gradient over the southern subtropical Indian Ocean, and eventually controlling the variability of the Indian Ocean summer monsoon (Hong et al., 2003).

Past variations in the monsoon strength can be assessed if we have specific proxies for the southwest monsoon (SWM, also known as the summer monsoon) and the northeast monsoon (NEM, also known as the winter monsoon), which we attempt here based on foraminiferal assemblages. In addition, the question of how the intensity of SWM affects the subsequent NEM and vice versa can be dealt with by understanding the long-term relationship between the two. In paleoclimatology, the causative factors of any climatic effect can only be understood if we have good temporal control i.e. robust chronology for the studied deep sea core with good proxy records which can be analyzed. Here we have analyzed a deep sea core with a well established chronology (Accelerator Mass Spectrometric (AMS) radiocarbon dates, calibrated) and good proxies i.e. planktic (i.e., living in the upper water column of the oceans) foraminifera, sensitive to variations in the strengths of the monsoons.

Modern abundances of specific species groups have been observed during the two monsoon seasons based on the Joint Global Ocean Flux Studies data (JGOFS) and sediment trap study (Curry et al., 1992). Thus applying the Huttonian principle of uniformitarianism, i.e., “present is the key to the past”, one can use the JGOFS data as far back as the Last Glacial Maximum (LGM) to decipher variations in the SWM and NEM separately based on variations in the planktic foraminiferal assemblages specific to the two monsoons. Here we present multi-proxy record from a gravity core collected from the present day open-ocean upwelling area, which is a suitable location for detecting the variation in the strength of both the monsoonal winds in the western Arabian Sea.

Rationale for Detecting Past Monsoon Signals

The integrity of each monsoon proxy depends on the extent to which it responds only to monsoonal wind forcing. If the proxy is also influenced by non-monsoon processes, then identifying and removing the unwanted signal (Wang et al., 2005) must be attempted. For inferring all these specific changes, planktic foraminifera have been found very useful. Planktic foraminifera respond to the monsoon induced upwelling and related hydrographic changes by showing significant changes in the relative abundances of certain species e.g. *Globigerina bulloides*, *Globigerinita glutinata* and many others (Naidu and Malmgren, 1995; Naidu and Malmgren, 1996a; Naidu and Malmgren, 1996b; Anderson et al., 2002; Gupta et al., 2003; Sinha et al., 2006). *Gg. bulloides* and *Ga. glutinata* are well established upwelling indicator planktic foraminiferal species whose abundances have been used by several workers to measure the strength of SWM winds (Curry et al., 1992; Anderson et al., 2002; Gupta et al., 2003; Gupta et al., 2005; Anderson and Prell, 1993). They are mostly abundant in water masses at high southern latitudes and have distinct maxima in high northern latitudes and low latitude upwelling regions (Thiede and Jünger, 1992) and in such cases their abundance can reach up to 60% (Anderson et al., 2002).

Globigerina bulloides is more abundant in central upwelling zones and areas of high productivity while *Ga. glutinata*, another upwelling indicator species is more frequently found at the margins of the upwelling areas (Brock et al., 1992; Hemleben et al., 1989; Sinha et al., 2006). Planktic foraminifera *N. dutertrei* prefer more stratified conditions with deep chlorophyll maxima (DCM) (Schiebel et al., 2001; Schiebel et al., 2004). During the NEM, entrainment of nutrients by deep wind-driven vertical mixing and winter cooling leads to enhanced primary productivity (Veldhuis et al., 1997). In addition, the stable isotope ratios ($\delta^{18}\text{O}$ and $\delta^{13}\text{C}$) of their calcite tests provide clues to infer the ocean water chemistry, sea surface temperature (SST) and productivity changes during monsoons (Hutson and Prell, 1980; Prell and Curry, 1981; Naidu and Malmgren, 1995, 1996; Anderson et al., 2002; Gupta et al., 2003; Gupta et al., 2005; Tiwari et al., 2010 and references therein).

Recently Ishikawa and Oda (2007) employed relative abundance variations of planktic foraminiferal species *Globigerina bulloides* and *Globigerinita glutinata* (typical for SWM upwelling) and *Neogloboquadrina dutertrei*, *Neogloboquadrina incompta*, *Globigerinoides ruber* and *Globigerinoides sacculifer* (typical for NEM

conditions) to decipher the monsoon-induced variability of oceanographic productivity in the open-ocean upwelling area in the northwestern Arabian Sea. The faunal record has been found to be quite reliable in interpreting the monsoon-induced upwelling, as there is no way other than upwelling by which the otherwise temperate species *Globigerina bulloides* can reach high abundance at low latitudes (Anderson et al., 2002). Further, the reliability of planktic foraminiferal species in general, and *Globigerina bulloides* in particular, as a proxy for the monsoon has been largely established by the Joint Global Ocean Flux Studies (JGOFS), designed to sample the sinking ocean sediments i.e. *ciadocoenosis* (Takahashi, 1995) in the water column at various depths and in different seasons (Curry et al., 1992). Here, we have generated planktic foraminiferal census counts and their stable isotopic records from a core whose location is under the influence of monsoon-induced upwelling and arrive at some robust interpretation with regard to the changing strength of the Indian monsoon during the last ~19 ka.

Material and Methods

A 1.3 m long gravity core, SS 4018G was collected in 1998 during the FORV *Sagar Sampada* cruise no. SS 164. The location is at the mouth of the Gulf of Aden (Figure 1, Table 1) in the western Arabian Sea. It was raised from a water depth of 2830 m, well above the lysocline in the Western Arabian Sea (~3900 m). The core was continuously sampled at every 2 cm. It contains exceptionally well preserved planktic foraminiferal assemblages. For census counts, foraminifera were separated from the sediments by shaking with distilled water and ½ mL of 30% H₂O₂ to oxidize any organic material present in the sediment sample. Wet sample was then warmed at 40°-45°C for an hour, after which foraminifera were separated out from the sediments by wet sieving. The >150 µm size fraction was chosen for census counts of planktic foraminifera, since this size fraction retains almost all the species; while cutting down on the juvenile tests that are hard to identify at species level and the entire

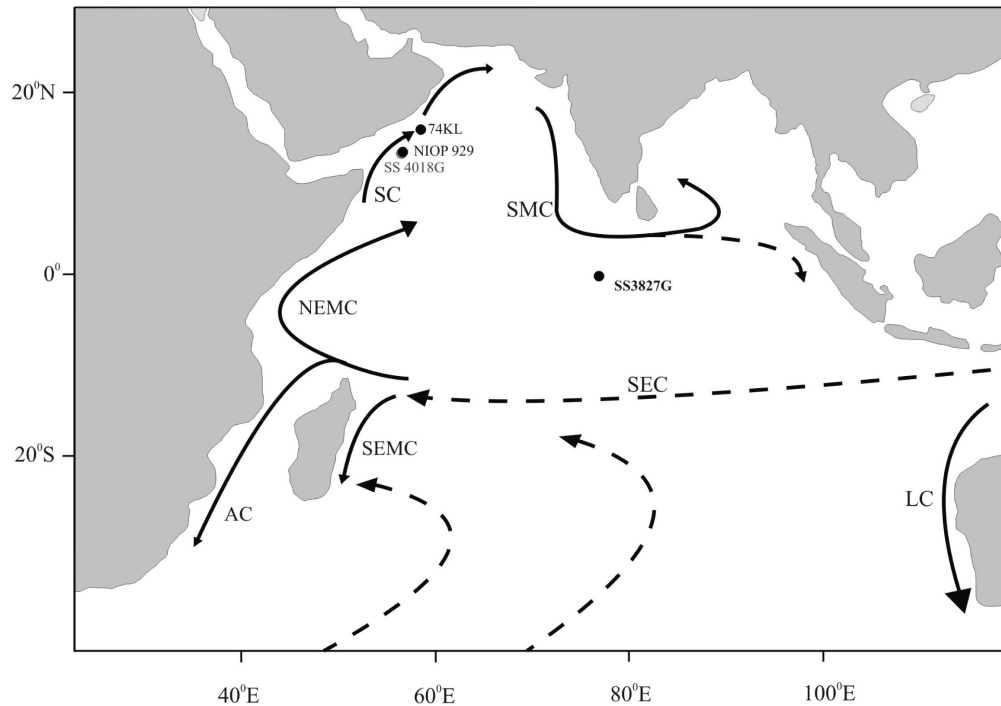


Figure 1: Surface hydrography in the Arabian Sea and location of site SS 4018G (solid circle, studied site) and other cores discussed in this paper: Core NIOP 905 (open circle, Saher et al., 2007); 126KL, Bay of Bengal (Kudrass et al., 2001); 74KL (Sirocko et al., 1996) and AAS 9/21, Eastern Arabian Sea (Govil and Naidu, 2010).

Table 1: Details of the core studied in this work

Core name	Type	Location lat., long.	Length (cm)	Water depth	Resolution	Age limit (a BP)
SS 4018 G	Gravity core	13°21.8'N, 53°15.4'E	130	2830 m	~150 years per cm	19,020

aliquot was mounted on assemblage slide for reference (Imbrie and Kipp, 1971; Wells et al., 1994). In the present study, the processed samples were split by an Otto microsplitter into suitable aliquots to get 300 or more individuals; each individual was identified up to species level following the taxonomy of Kennet and Srinivasan (1983) and Bolli and Saunders (1985) for census counts. The remaining aliquot was used for stable isotopic studies and to establish depth stratified assemblages of planktic foraminiferal species to decipher the hydrographic changes in upper ocean water column in response to monsoons.

The knowledge of depth stratified assemblages has been mainly obtained from data based on JGOFS and stable oxygen isotopic depth ranking of individual species (Gasperi and Kennett, 1992; Chaisson and Ravelo, 1997). The oxygen and carbon isotope compositions of the planktic foraminiferal species, *Globorotalia menardii* (thermocline dweller) and *Globigerinoides ruber* (white variety, surface dweller) from 250–450 μm size fractions were carried out on a Europa Scientific GEO 20-20 stable isotope ratio mass spectrometer with an online acid preparation device at the Physical Research Laboratory, Ahmedabad. The stable isotope data are reported in delta (δ) notation relative to the V-PDB standard. Reproducibility of $\delta^{18}\text{O}$ is $\pm 0.1\text{‰}$. Errors quoted are 1σ standard deviation. The chronology of the core was established by 15 radiocarbon dates (Table 2) obtained on handpicked species of planktic foraminiferal species *Gs. ruber*, *Gs. sacculifer*, *O. universa* and *N. dutertrei* in the size range 250–500 μm . The dating was done at the Accelerator Mass Spectrometer NSF Facility, University of Arizona, USA (Tiwari et al., 2010). The sediment accumulation rate at the core location is ~ 7 cm/kyr.

Present Oceanographic Conditions at the Core Site

The core SS4018G is largely influenced by the western arm of the Great Whirl (GW) and associated upwelling wedge (Schott and McCreary, 2001) during SWM (Figure 1). The GW is a result of strong northward flowing Somali Current (SC). However during NEM the GW together with the associated upwelling wedges disappears due to reversal of the SC. South Equatorial Current (SEC) supplies the water from the Pacific Ocean to the Indian Ocean via Indonesian through flow, which is relatively warm in comparison to the Indian Ocean. The SEC splits into two branches at the tip of Madagascar at 17°S , and the northward flowing

branch Northeast Madagascar Current (NEMC) feeds the northward flowing East African Coast Current (EACC). During SWM the EACC feeds the northward flowing Somali Current that leads to the development of intense upwelling due to the Ekman transport from the Somalian and Oman coast (Schott et al., 1990; Brock et al., 1991) and the upwelling velocities close to 3×10^{-3} cm/sec and an upwelling transport of 1.5–2 Sv occurs in the upper 50 m (Smith and Bottero, 1977; Shi et al., 2000). The typical temperature of the upwelled water is $19\text{--}23^\circ\text{C}$ (Schott and McCreary, 2001). During the winter monsoon, the Somali Current reverses its direction and flows southward and meets the EACC at $2\text{--}4^\circ\text{S}$ that supplies the eastward flowing South Equatorial Countercurrent (SECC) (Dueing and Schott, 1978; Swallow et al., 1991). The cold and dry Northeast monsoon wind accompanied by the Ekman pumping inhibits upwelling the northern Arabian Sea (Morrison, 1997; Schott and Fisher, 2000; Schott and McCreary, 2001). The cold wind-induced convective overturning supports a reduced productivity in comparison to SWM (Banse and McClain, 1986; Madhupratap et al., 1996).

Results

Planktic Foraminiferal Record

The planktic foraminiferal assemblage in core SS 4018G largely consists of tropical water mass species including *Globigerinoides ruber*, *Gs. conglobatus*, *Gs. sacculifer*, *Gs. triloba*, *Globorotalia menardii*, *Gr. Tumida* and *Orbulina universa* with episodic invasion of upwelling species *Globigerina bulloides*, *Globigerinita glutinata*, *Neoglobobadrina dutertrei* etc. These species are found to live in different depths in the open ocean e.g. *Globigerinoides ruber*, *Gs. conglobatus*, *Gs. Sacculifer* and *Gs. triloba* are mixed layer dwellers (MLD) while *Globorotalia menardii*, *Gr. Tumida* and *Pulleniatina obliquiloculata* are thermocline dwellers (TDS). The census data shows a remarkable degree of fluctuation in the relative abundance of depth stratified assemblages indicating changing hydrography in the upper ocean induced by varying monsoon winds. The upwelling species occasionally reach as high as ~ 40 to 50% of the total assemblage which shows a good correlation with the Total Organic Carbon (TOC) record from the same site (Tiwari et al., 2010) (Figure 2).

In the score analyzed, both *Globigerina bulloides* and *Globigerinita glutinata* (upwelling indicator species, UIS) and *Globigerinoides* group (mixed layer dweller, MLD) show significant variations from 19 ka till 5 ka and subsequently, the amplitude of variation is reduced.

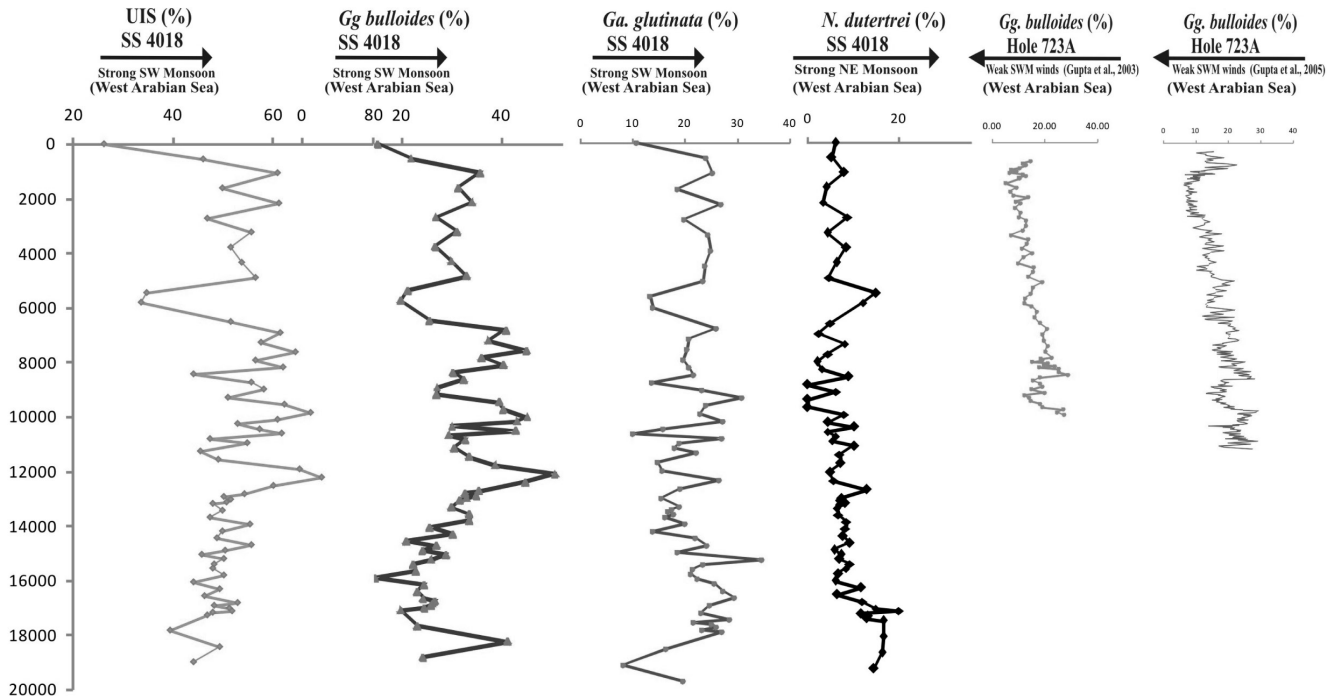


Figure 2: Plot of relative abundance of upwelling indicator *Gg. bulloides*, mixed layer dweller (*Globigerinoides*), Thermocline dweller *Gr. menardii*, *N. dutertrei*, Total organic carbon (Tiwari et al., 2010) and $\delta^{18}\text{O}$ values of *Gs. ruber*. SWMI = Southwest Monsoon Mode; SWMD = Southwest Monsoon decrease, NEMI = North East monsoon intensification.

The proportion of *Globigerina bulloides* ranges from ~15 to 50% of the total assemblages, while those of MLD from 10 to 30% (Figure 2).

In general, the peaks of abundances of *Globigerina bulloides* and *Ga. glutinata* (both UIS) match with the low abundance peaks of MLD. We observed eight intervals of major change in the abundance of these two important species from 19 ka to 5 ka. *Globigerina bulloides* shows increasing trends around ~16-12.5 ka and ~10-8 ka while the MLDs show increasing trend during ~17-16 ka, ~12-11 ka, ~9.7-8.2 ka and ~7.8-5.4 ka. We have also observed the enhanced abundance of NEM indicator planktic foraminiferal species *Globigerinoides sacculifer*, *Gs. obliquus*, *Gs. triloba* and *Neogloquadrina dutertrei* (Figure 2), which suggests the strengthening of NEM winds during ~19-17 and 7.8-5.4 ka relative to the present, marked as NEMI-I and II. From 5.4 ka onwards the *Gg. bulloides* values show low relative abundances maintaining constant values till 1.2 ka and thereafter further decrease till the present (Figure 2).

Oxygen Isotope Record

Stable oxygen isotope record ($\delta^{18}\text{O}$) of *Globigerinoides ruber* (mixed layer dweller) and *Globorotalia menardii*

(thermocline dweller) show long term (multi-millennial) trends superimposed on short term (multi-centennial) excursions (Figure 2). Oxygen isotopes are affected by the ice-volume effect, SST changes (due to upwelling of cold water during SWM), and Evaporation-Precipitation (E-P) balance (that alters the $\delta^{18}\text{O}$ value of surface seawater). In the core analyzed, distinct global melt water signal (ice-volume effect) is recorded by the oxygen isotopes of planktic foraminifera, superimposed by E-P and SST (upwelling) related changes. Recently Saher et al. (2007a) reconstructed SST, based on Mg/Ca of planktic foraminifera, from core NIOP 929 in Western Arabian Sea very near to the site of the present study. We have used it to filter out the effect of SST from the $\delta^{18}\text{O}$ record of the present study. The contribution of ice-volume effect has been subtracted based on the sea-level curve by Fairbanks (1989) and Peltier and Fairbanks (2006). From ~19 ka to ~14 ka (Termination IA; Bard et al., 1987), global seawater $\delta^{18}\text{O}$ decreased by 0.25‰ (ice-volume effect (Fairbanks, 1989; Peltier and Fairbanks, 2006) and SST at the core site increased by ~2°C (Saher et al., 2007a) accounting for a decrease of 0.5‰ in $\delta^{18}\text{O}$ (Erez and Luz, 1983). In SS 4018G, $\delta^{18}\text{O}$ decrease is ~1‰ during this period; the remaining ~0.25‰ decline in foraminiferal $\delta^{18}\text{O}$

can be due to excess of precipitation over evaporation during that period, which indicates the beginning of the re-establishment of the SWM mode. It matches well with the percentage population of *Gg. bulloides* during that period indicating the post-LGM beginning of SW monsoon mode (SWMI-I).

The increase in $\delta^{18}\text{O}$ was $\sim 1\text{‰}$ for *Gs. ruber* and $\sim 0.6\text{‰}$ for *Gr. menardii* (Figure 2) during the Younger Dryas (12.5 ka to 11.5 ka). The global seawater $\delta^{18}\text{O}$ reduced by 0.15‰ during this time, thus the total increase in $\delta^{18}\text{O}$ values of the foraminifera were $\sim 1.15\text{‰}$ and 0.75‰ for *Gs. ruber* and *Gr. menardii* respectively. The probable reasons for such an increase can either be enhanced upwelling affecting the SST or enhanced E–P balance. The first would have affected both the species equally. But the surface dwelling species show higher values, indicating a surface phenomenon i.e. an excess of evaporation over precipitation. After 12.5 ka, the relative abundance of *Gg. bulloides* shows a rapid decline indicating reducing monsoon in response to Younger Dryas cooling. Overall $\delta^{18}\text{O}$ values were higher during glacial period relative to the Holocene indicating the reduced precipitation.

Global ice–volume effect was only $\sim 0.15\text{‰}$ from 10–9 ka. But *Gs. ruber* exhibits a sharp reduction in $\delta^{18}\text{O}$ values by $\sim 1\text{‰}$ that indicates copious monsoon precipitation and hence intensified SWM mode then. This is supported by several other studies that exhibit early Holocene monsoon maxima (Sirocko et al., 1993; Overpeck et al., 1996; Gupta et al., 2003; Morrill et al., 2003; Saher et al., 2007a).

During the rest of the Holocene, we observe that $\delta^{18}\text{O}$ trends for both the foraminiferal species stay more or less uniform within the errors. Such an unvarying trend during the Holocene has been observed by various other studies such as (Erez and Luz, 1983; Staubwasser et al., 2002; Tiwari et al., 2010). Annual average SST reconstruction on *Gs. ruber* in western Arabian Sea by (Saher et al., 2007a; Saher et al., 2007b; Anand et al., 2008) showed, during the Holocene, rapid centennial scale fluctuations of $1\text{--}2^\circ\text{C}$ but does not exhibit any long-term trend. The $\delta^{18}\text{O}$ record (Saher et al., 2007a, b) also remains more or less uniform during the Holocene, similar to our observations. Saher et al. (2007b) reconstructed the $\delta^{18}\text{O}_{\text{water}}$ that indicates sea surface salinity (SSS) by subtracting the effect of SST (reconstructed using Mg/Ca) from the $\delta^{18}\text{O}_{\text{calcite}}$. They also observed that since ~ 8 ka, salinity also stays more or less uniform indicating unvarying, moderate (in comparison to early Holocene) SWM mode. It corroborates the results from % *Gg. bulloides*

that display an unvarying trend since 6 ka indicating a moderate SWM mode.

Discussion

Early Deglacial Phase (19–17 ka)

After LGM, at $\sim 19\text{--}17$ ka (the early deglacial phase), there has been a significant increase in relative abundance of *N. dutertrei* indicating higher NEM strength (Figure 2). This short spell of strengthening NEMI-I of the northeast monsoon during $\sim 19\text{--}17$ ka was also documented by Sirocko et al. (1993, 1996) as Event-I, based on low dolomite flux at core 74KL from the upwelling region of the western Arabian Sea (close to the site of SS4018). Tiwari et al. (2005b), also recorded the NEM intensification during same time from equatorial Indian Ocean on the basis of $\delta^{18}\text{O}$ analysis of species of planktic foraminifera which revealed that the NEM strengthened during the early deglacial period. A second centennial-scale high SST/low $\delta^{18}\text{O}$ event is observed at 17 ka, which are referred to as Arabian Sea Warm (ASW) Event-II and ASW-I (Saher et al., 2007a). They noted an early onset of the temperature rise. They have also noted a high productivity during this interval, however they left this question unanswered as to how in an upwelling regime, high SST and high productivity (obviously caused by upwelling) can co-occur, though they provided an explanation of increasing Trade Winds (Bush and Philander, 1998; Jung et al., 2004) bringing warm waters to the Arabian Sea as a plausible mechanism of their ASW events. Here, based on significant increase in *N. dutertrei* and *Globigerinoides* group (MLD) abundance and high TOC and C/N ratio, reported from the same core by Tiwari et al. (2010), we provide an explanation for the high productivity observed during ASW-2 by Saher et al., (2007a). This increase in abundance in the *N. dutertrei* and MLD population could be due to the strengthening of NEM winds. This interval of increased NEM strength has been marked as NEMI-I (Northeast Monsoon Mode Increase) in Figures 2 and 3. From 17 to 16 ka the relative abundance of *Globigerina bulloides* shows a sharp decline from 50 to 15% (Figure 2) inferred as an interval of weaker SWM monsoon. The percentage increase in MLDs during this interval further supports a thick mixed layer and water mass stratification. This event has been designated as SWMD-I. At 16 ka Saher et al. (2007a) observed the lowest productivity from the core NIOP929 and high SST. TOC data from the studied core (Tiwari et al., 2010) data also shows the lowest productivity at ~ 16 ka (Figure 3).

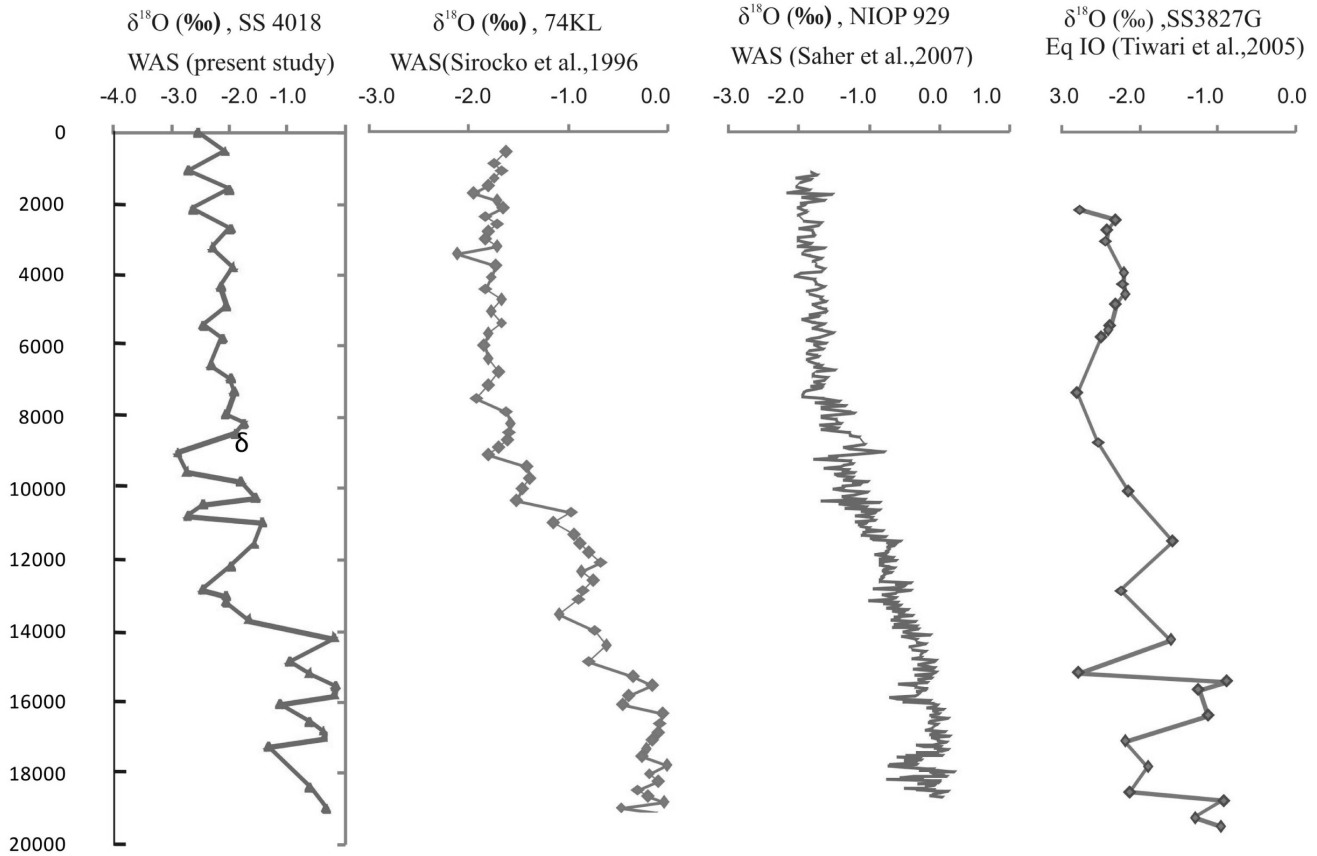


Figure 3: Comparison of: (a) Down core sea surface salinity variation records of core 126KL from the proximal end of Bay of Bengal (Kudrass et al., 2001), (b) Temporal variations in *Gg. bulloides* (UIS), (c) Mg/Ca records from core NIOP 965, WAS (Saher et al., 2007a), (d) Mg/Ca records from core AAS 9/21, EAS (Govil and Naidu, 2010) and (e) SST records from core 126KL from Bay of Bengal (Kudrass et al., 2001).

Late Deglacial Interval (17-12.5 ka)

From ~16 to ~12 ka there is an observable increasing trend in the relative abundance of *Globigerina bulloides*, from 15 to 50% of the total assemblage, with a peak at ~12.5 ka. The interval (14-12 ka) is also marked by very low abundance of MLDs indicating mixing of surface and thermocline waters due to enhanced upwelling and loss of water mass stratification. This interval (SWMI-II) is interpreted to show a stronger SWM. Sirocko et al. (1993) observed their Event 3 of decreased dolomite content at ~16 ka linked to enhanced SWM. These authors also explained the possible linkages of deglacial event and monsoon strength through changes in albedo; induced by changing snow cover which exerts considerable control over the development of continental heat low over mainland Asia, affecting SWM over the Arabian Sea (Kutzbach and Guetter, 1986; Barnett et al., 1989; Lautenschlager and Santer, 1991). At the same time from the eastern Arabian Sea (EAS), Govil et al. (2008) reported the enhanced SWM

during 16-12 ka on the basis of negative excursion in the $\delta^{18}\text{O}$ record. This record from EAS is in good accordance with the increase in relative population of *Gg. bulloides* from WAS observed in the present study. Kudrass et al. (2001) reported that the large river system from the Indian sub-continent (e.g. Ganga-Brahmaputra) drains as much as 50,000 m³/s of water and the high fresh water flow reduces the salinity. They also reported (Figure 4) oscillation of $\delta^{18}\text{O}$ record during the transition from LGM to Holocene due to stepwise reestablishment of summer monsoon.

Younger Dryas (YD)

Before the beginning of Holocene and during last phase of Younger Dryas ~12.5-11 ka, we observe a decline in the relative abundance of *Globigerina bulloides* (50 to 30%), indicating a weakening of SWM (SWMD-II), also supported by $\delta^{18}\text{O}$ data. Earlier, several workers observed an obvious abrupt weakening of SWM during the YD cold event (Gasse et al., 1991; Roberts et al.,

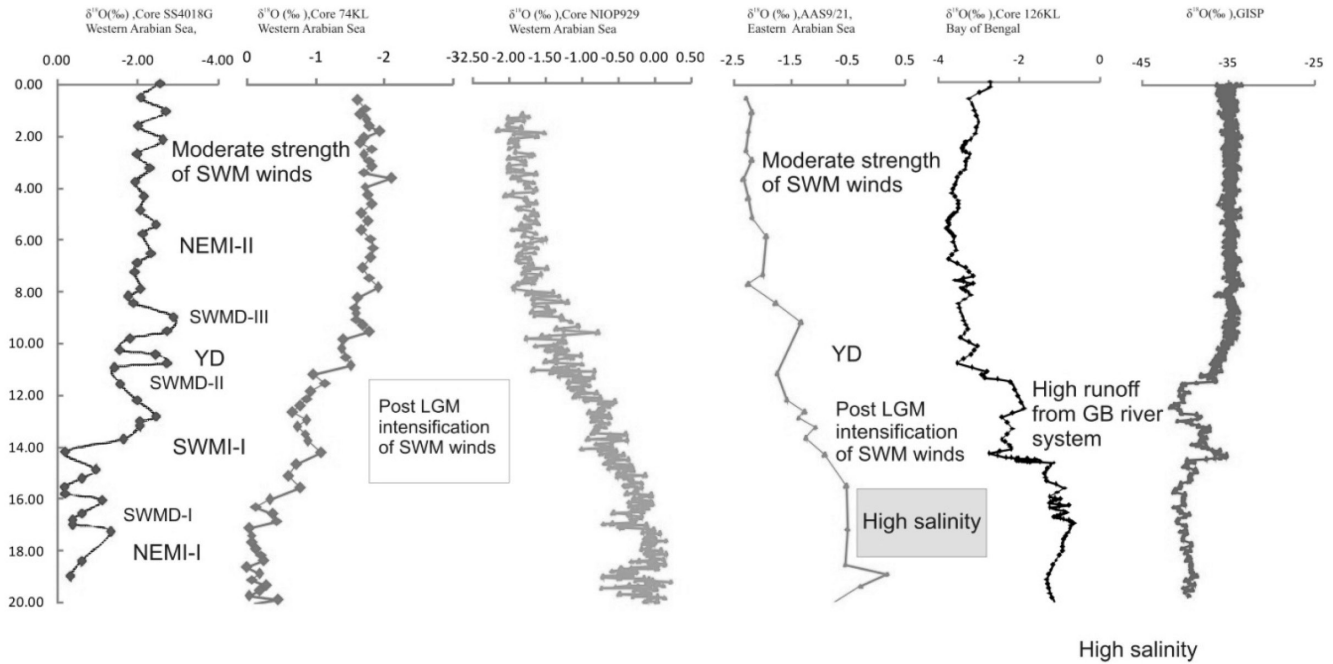


Figure 4: (a) The oxygen isotope profile of *G. ruber* ($\delta^{18}\text{O}$) from the core SS 4018G, WAS, (b) Oxygen isotope profile of *G. ruber* ($\delta^{18}\text{O}$) for core 74KL, WAS (Sirocko et al., 1996), (c) Oxygen isotope profile of *G. ruber* ($\delta^{18}\text{O}$) for core NIOP (Saher et al., 2007a), (d) Oxygen isotope profile of *G. ruber* ($\delta^{18}\text{O}$) for core AAS 9/21, EAS (Govil and Naidu, 2010), (e) Oxygen isotope profile of *G. ruber* ($\delta^{18}\text{O}$) for core 126KL, BOB (Kudrass et al., 2001) and (f) Oxygen isotope profile of ice core GISP.

1993; Sirocko et al., 1996; Schulz et al., 1998). Several mechanisms have been hypothesized (Bond et al., 2001; Bond and Lotti, 1995; Bond et al., 1997; Broecker, 2003; Clement and Peterson, 2008; Hong et al., 2003; Hong et al., 2009) to explain this teleconnection between North Atlantic climate variability and SWM. These include variation of ocean thermohaline circulation (THC) in the Northern high latitudes driving of the ocean–atmosphere interaction in low latitudes, the variation of solar activity and the movements of the ITCZ, and the combined effect of solar activity, THC, and ENSO (Hong et al., 2010). This event has been designated as SWMD-II and is correlated to Younger Dryas cold event.

Holocene: Interglacial Interval

During earliest part of Early Holocene, the relative abundance of *Globigerina bulloides* (Figure 5) indicates strengthening of SWM; we have termed this as the post Younger Drays intensification of SW Monsoon culminating ~10 ka and designated it as SWMI-II. This event has also been observed by Hong et al. (2003). Based on climatic proxy records of lake sediments from the Sanjiaocheng section located at the NW boundary of the summer monsoon, Gansu Province, Fahu et al. (2001) interpreted that the early Holocene was humid with stronger summer monsoon. Around ~10 ka,

Bookhagen et al. (2006), observed the early Holocene Indian Summer Monsoon (ISM) precipitation enhanced and amplified sediment flux from these areas caused alluviation of downstream valley upto 120 m above the present level. This is followed by a short spell of decreased SWM around 9.7 ka to 8.2 ka (SWMD-III).

We have also identified a period of enhanced NEM winds during ~7.8–5.4 ka marked as NEMI-II in Figure 5. During this interval other thermocline dweller species also show increasing trends in their population. *Globigerinoides* sp. has been identified in time-series fluxes during non-upwelling periods in the open Arabian Sea (Curry et al., 1992). Conan and Brummer (2000) reported that the relative abundance of *Gs. ruber* and *Gs. sacculifer* increased during the non-upwelling NE monsoon season, at that time warm mixed layer developed with the nutrient entrained by deep water mixing. *Gs. ruber* and *Gs. sacculifer* behave as perennial species in all seasons (Curry et al., 1992); therefore the observed increase in the relative abundances of *Gs. ruber* and *Gs. sacculifer* during ~7.8–5.4 ka (Figure 5) suggests the dominance of NEM and reduced upwelling at the core SS4018G. This event shows a major decline in the upwelling intensity during ~7.8–5.4 ka revealed by the sharp decline in the UIS from 70% to 30% (Figure 5) and during the same interval NEM indicator species

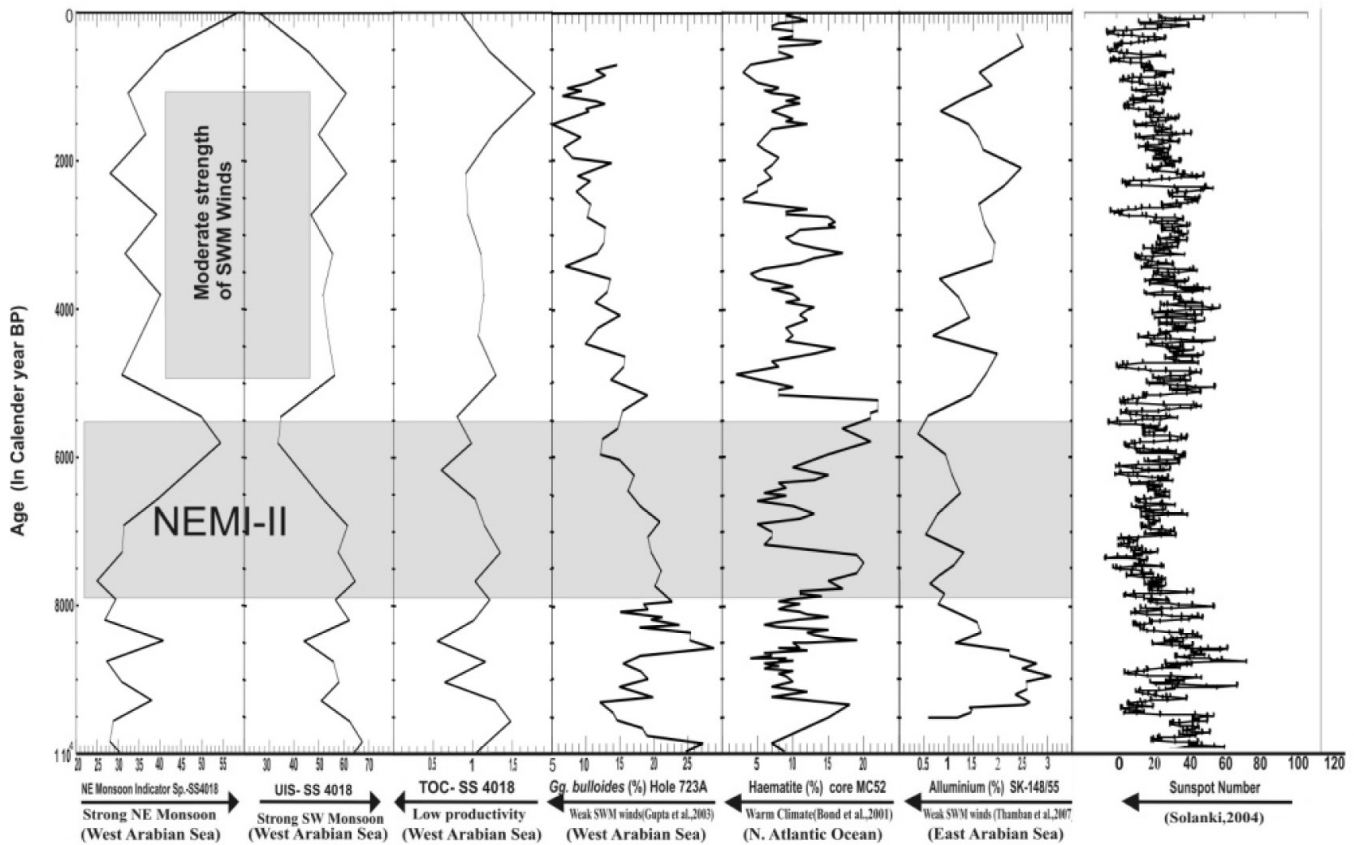


Figure 5: Comparison of available data: Temporal variation in (a) north east monsoon indicator species with (b) Southwest monsoon indicator species (present study), (c) Total organic matter content (Tiwari et al., 2010), (d) relative abundance of *Gg. bulloides* from core 763A, WAS (Gupta et al., 2003), Terrigenous proxy records, (e) Hematite (%) variation records from core MC52, from North Atlantic (Bond et al., 2001), (f) Variation records in Al (%) from core SK 148/55 (Thamban et al., 2007) and (g) Sun Spot data (Solanki et al., 2004).

shows very high abundance reaching from 30% to 55% of the total assemblage (Figure 5).

The other important proxy, Total Organic Carbon (TOC) from this site (Tiwari et al., 2010) shows low values during this interval—a decline from 1.5% to 0.5% (Figure 3). The TOC record also suggests low productivity and reduced upwelling condition because of weak SWM winds. Gupta et al. (2003) and Gupta et al. (2005) also reported weak SWM winds at 6.2–5.5 ka (Figure 6) in the western Arabian Sea and correlated them with the North Atlantic cold events (Bond events 5 and 4 occurred at ~6.2 to 5.4 ka) which was marked by the higher percentage of hematite stained grains reported by Bond et al. (2001) (Figure 5). At the same time from Eastern Arabian Sea (EAS), weakening in precipitation was recorded at ~7.0 ka and the most significant weak SWM was recorded during 6.0–5.5 ka (Conan and Brummer, 2000; Sarkar et al., 2000; Thamban et al., 2001; Thamban et al., 2002; Thamban et al., 2007).

Webster et al. (1998) suggested that the monsoon oscillates between several basic states under the influence of remote forcing induced by SST or land surface conditions. It is worthwhile to discuss here the causative factors for enhanced strengths of SWM and NEM since the LGM. Though there have been a number of causative factors for the variability of the Asian monsoon intensity, a few workers have correlated this variability to the North Atlantic cold events (Raman and Malekal, 1985; Bond and Lotti, 1995; Gupta et al., 2003; Wang et al., 2005). A comparison with the chronology of the North Atlantic cold events and the discussed event suggests that there may be a linkage as observed earlier. During the ~8.0–5.5 ka event, N. Atlantic region was experiencing the cold climate suggested by the occurrence of the highest amount (22%) of hematite-stained ice rafted debris (IRD) in the discharge of debris-laden icebergs from the east central coast of Greenland (Bond and Lotti, 1995;

Bond et al., 1997; van Kreveld et al., 2000; John et al., 2004). At the time of prolonged winters, ITCZ shifts towards south and the NE monsoonal wind helps in the convective mixing in the mixed layer of the Western Arabian Sea water which is manifested by the presence of higher abundance of thermocline and warm mixed dweller planktic foraminiferal species during 8.0-5.4 ka (Figure 5).

Recently, workers like Solanki et al. (2004), Gupta et al. (2005) and Tiwari et al. (2005a) discussed the effect of solar influence on the strength of SWM during Holocene. Solanki et al. (2004) reported the weakening in the insolation during Holocene on the basis of reduction in the sun spot numbers. This shows the good correlation with the N. Atlantic cooling events observed by Bond et al. (2001) and also with the increase in the concentration of cosmogenic nuclides ^{14}C and ^{10}Be in polar ice cores. Low insolation affects the movement of the ITCZ that controls the monsoonal winds. Fleitmann et al. (2003) inferred a continuous southward migration of the mean summer ITCZ, a gradual weakening of summer monsoon after 8 ka in response to a declining June to August summer insolation at 30°N (Paillard et al., 1996; Berger and Loutre, 1991). This insolation related weakening of summer monsoon caused by southward migration of ITCZ has also been found for tropical South America based on Ti content (Fleitmann et al., 2003; Haug et al., 2001). Land based record also suggest the low SWM precipitation on the basis of lack of terrace formation (Bookhagen et al., 2005; Bookhagen and Burbank, 2006).

Conclusions

Based on multi-proxy analysis, three intervals of increased Southwest Monsoon Mode have been inferred at ~16 to 12 ka (SWMI-I), ~10 ka (SWMI-II) and ~8.2-8.0 ka (SWMI-III). These intervals are bridged by decline in Southwest Monsoon: SWMD-I (~17-16 ka), SWMD-II (~12-11 ka) and 9.7 ka to 8.2 ka (SWMD-III). After attaining an early Holocene maximum, SW monsoon attains a moderate mode and stays more or less uniform during the rest of the Holocene.

Two intervals of increased Northeast Monsoon Mode (winter monsoon) have been observed around 19-17 ka and NEMI-II (~8.0-5.4 ka).

We propose that the number of factors affect the intensity of both SWM and NEM pattern in the western Arabian Sea. During Holocene, especially during 8.0-5.5 ka, NE monsoon intensified because of variability in the insolation, which helped in the development of

cold events at high latitude regions like N. Atlantic cold events (Bond cold events).

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