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Recently Studied Sedimentary Records from the Eastern Arabian Sea: Implications to Holocene Monsoonal Variability

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Abstract

Deep insight into exact mechanism(s) controlling past monsoonal variability on inter-annual to millennial time scales is a pre-requisite for developing predictive capability of monsoon on timescales relevant to human life. Reliable monsoon predictions developed by climate modelers play a crucial role for making country's future economic programme. Basic data input to generally applied monsoon models is instrumental rainfall data, beyond which search for monsoon variability relies upon proxy records stored in various natural repositories such as tree rings, corals, cave deposits, lake and marine sediments. While tree rings, cave deposits and corals are capable of yielding paleo-monsoonal information on extremely high temporal resolution, continental margin sediments depositing in the Arabian Sea have provided relatively coarser but longer proxy records of monsoonal variability. Here we review some of such recently studied sedimentary records from precipitation dominated eastern Arabian Sea in an attempt to comprehend past monsoonal variability in Indian as well as global context. We also focus upon different proxies used so far in the Arabian Sea, their fidelity, limitations and future scope of using novel proxies for a better understanding of past monsoonal variability especially in the anthropocene epoch.

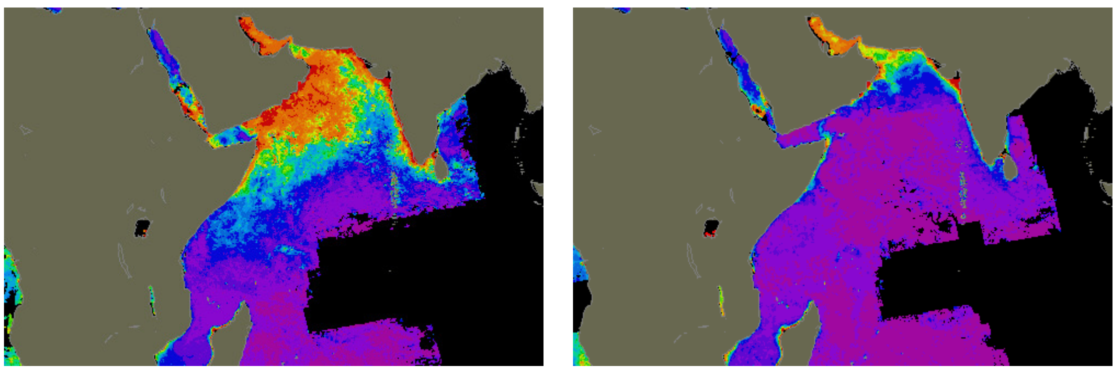
Introduction

Knowledge of past monsoon variability has been an immensely studied research area attracting inter-disciplinary scientists since long, owing to its socio-economic significance for monsoon affected and densely populated countries on Indian sub-continent *e.g.* India, Pakistan, Sri Lanka and Bangladesh. Instrumentally measured All India Summer Monsoon Rainfall (AISMR) data spanning last 130 years (Parthasarathy *et al.,* 1995) have been available to scientific community; however, to develop realistic and adaptable monsoon models, natural variability of south Asian monsoon (or southwest monsoon) has to be known beyond the anthropogenic era. This requires a wide-ranging search for monsoon variability stored in various natural repositories such as tree rings, corals, cave deposits, lake and marine sediments in the form of different biological, geological and chemical proxies. Quality and applicability of paleo-monsoonal research beyond the instrumental era is strongly dependent on choice of repository, location, sampling resolution and fidelity of the used 'proxy'. Though some of the continental and shallow marine repositories (cave deposits, tree rings, corals, for example) do provide extremely high temporal resolution varying from weekly to annual time scale, these proxy records at times are strongly influenced by 'local' rather than 'regional climate' and in turn possess significant 'noise'. These proxy based monsoonal reconstructions are also often limited in total time-stretch requiring a substantial patch work (time series alignment) to yield an integrated monsoonal variability of a particular region.

In contrast, well dated sedimentary records preserved in oxygen deficient waters (oxygen minimum zone; OMZ) of the Arabian Sea have shown their capability to catalogue the global monsoonal variations on annual to orbital time scales (Schulz *et al.,* 1998; von Rad *et al.,* 1999; Suthhof *et al.,* 2001; Lückge *et al.,* 2001; Altabet *et al.,* 2002; Agnihotri *et al.,* 2002; Anderson *et al.,* 2002; Gupta *et al.,* 2003) relatable to global climate. It is important to state here itself that, depending on the locale and context, usage of the monsoonal term is also adapted. For example, the broad south Asian monsoon term signifies itself as southwest (SW;

henceforth) monsoon or northeast (NE; henceforth) monsoon for all the paleoceanographic studies implicating to past monsoonal variability in the Arabian Sea.

Sediments depositing beneath OMZ of the western Arabian Sea have been extensively exploited for paleo-monsoon reconstructions owing to the following facts (i) surface biological productivity and associated biogeochemistry of the region substantially responds to seasonal reversal of monsoonal winds (Fig. 1) (ii) higher sediment accumulation rates enable sediments to record short term (decadal to centennial scale) climatic oscillations in conventionally analyzable mm to cm slices and (iii) presence of thickest OMZ in water column extending from ~200 to 1200m (Naqvi, 1987) probably help better preservation of various biogenic (organic and inorganic) proxies with minimal particle reworking through bioturbation.



(a) (b)

Fig.1: Satellite pictures of the Arabian Sea revealing seasonal contrast of surface biological productivity during (a) SW monsoon (left) and (b) Non-monsoon season (right). Red & green colors indicate regions of high surface productivity, while blue and purple colors represent low productivity conditions (pictures are taken from http://daac.gsfc.nasa.gov)

Despite voluminous temporally well-resolved proxy data available from sediments of the Arabian Sea especially from western and northwestern side, there is neither a uniform picture of past monsoonal variability emerged out, even for the 'traditionally thought' stable climatic period *i.e.* the Holocene (last ~10,000 years), nor a unanimously preferred 'proxy' for reconstructing paleo-monsoon variability has been suggested. Moreover, as the case for the modern climate, paleoceanography of the western and northwestern sides of the Arabian Sea is dominated by intense monsoonal winds and associated upwelling resulting in high surface biological productivity (Prell, 1984; Sirocko *et al.,* 1993, 1996, 2000; Reichart, 1997; Anderson *et al.,* 2002; Gupta *et al.,* 2003) rather than precipitation. Therefore, it is always a pertinent question about utility of these paleo-monsoonal reconstructions in terms of their applicability in models dealing with monsoonal precipitation on Indian sub-continent. On the other hand, too few well-dated proxy records are ironically available from the precipitation dominated eastern Arabian Sea (Sarker *et al.,* 2000; Agnihotri *et al.,* 2002, 2003 a & b; 2008a; Thamban *et al.,* 2001 & 2007; Kurian *et al.,* 2008) to provide desired basic data input to monsoon models. In contrast to western Arabian Sea, where biogenic and eolian proxies have been quite successfully employed (Sirocko *et al.,* 2000) and paleo-monsoon variability in terms of monsoonal winds have been reconstructed ranging from last few centuries to more than ~200 ka BP (Reichart *et al.,* 1998; Anderson *et al.,* 2002), the eastern Arabian Sea, in general, receives very less dust input from Indian sub-continent and upwelling induced surface productivity is also limited to mainly coastal regions off Pakistan and western coast of India. Nonetheless, eastern part of the Arabian Sea is the only locale in the Arabian Sea where heavy precipitation takes places on all along the west coast (~300-400 $cm.a^{-1}$) during SW monsoon (Fig. 2).

This results in large amount of continental runoff influencing coastal hydrography significantly traceable on a seasonal basis. Precipitation on west coast of India systematically increases from Gujarat to Kerala coast by ~350 mm. $(\text{degree latitude})^{-1}$ (Sarkar *et al.,* 2000). In addition to precipitation, conspicuous surface biological productivity can also be seen on all along the west coast of India during SW monsoon (Fig.1a). Besides these natural manifestations of SW monsoon, increasing anthropogenic activity in the urban and relatively developed west coast of India has been proposed to be capable of perturbing coastal ecology/ biogeochemistry of the region (Naqvi *et al.,* 2000; 2006 a,b). Interestingly and probably unique in the world, anthropogenic activity is also manifested here (the eastern Arabian Sea) via a dominant natural forcing *i.e.* the SW monsoon. Thus, eastern Arabian Sea presents itself as a unique locale for paleo-monsoonal reconstructions ideally suited for delineating anthropogenic versus natural (SW monsoonal) forcing by studying temporally well-constrained and well resolved sedimentary records with suitable proxies and their inter-comparison with other contemporaneous global climate data archives. Fidelity of various proxies can also be tested by comparing proxy time series with available modern instrumentally measured climate parameters such as rainfall, sea surface temperatures etc.

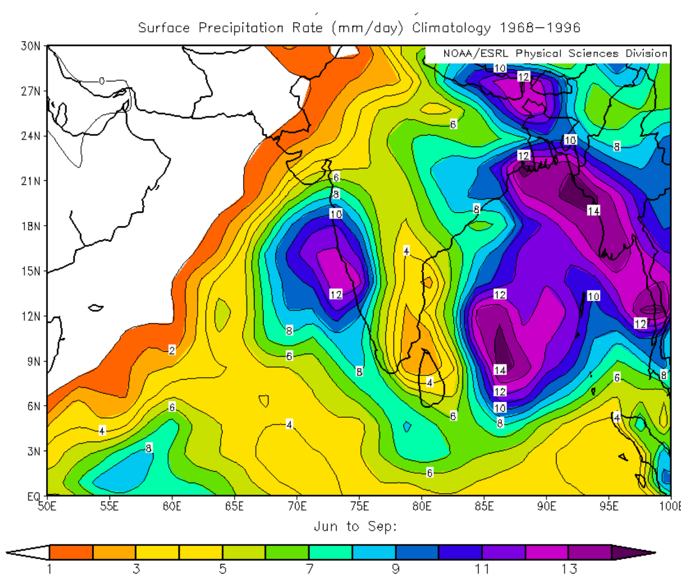


Fig.2: Surface precipitation map generated by satellite measurements clearly demonstrate eastern Arabian Sea as a precipitation dominated region. Area off Konkan-Goa coast and Karnataka receive high precipitation during SW monsoon season.

Despite these great potentials, sedimentary archives stored in the eastern Arabian Sea have not been extensively explored yet. Nonetheless, available quality monsoonal reconstructions from this region on varying timescales (decadal to millennial) have provided paleo-monsoonal history in terms of changes in hydrological cycle, which is conspicuously different than that obtained by wind intensity records (especially in Holocene), underscoring importance of the eastern Arabian Sea for paleo-monsoonal research. We review here some of recently studied such proxy records from the eastern Arabian Sea and also explore possibility of new proxies in conjunction with usually employed ones for monsoonal reconstructions in this region. We mainly focus here on high-resolution (decadal to centennial) paleo-monsoonal records spanning Holocene with special emphasis on the last millennium (last ~1000 years) and the Anthropocene epoch (the last ~100-150 years) in order to characterize most dominant natural forcing on SW monsoon variability just before the advent of greenhouse era. We first briefly discuss hydrography of the eastern Arabian Sea in response to SW monsoon and applied major proxies in the paleo-monsoonal research carried out so far.

Hydrography of the eastern Arabian Sea

Coastal circulation along the west coast of India as elsewhere in the North Indian Ocean, reverses annually during April and October associated with the two monsoons (Shetye and Gouveia, 1998; Naqvi *et al.,* 2006a,c). In winter (NE monsoon), the West India Coastal Current (WICC) flows poleward, causing downwelling and well-oxygenated conditions in the water column over the shelf. In contrast, circulation in summer (SW monsoon) is typical of an eastern boundary –an equator-ward flowing WICC, a pole-ward undercurrent and coastal upwelling. In addition, the entire west coast receives large precipitation as high as ~400 cm during just four summer months between June and September. The freshwater inputs result in very strong but shallow thermohaline stratification; yet, the high nutrient concentrations in the freshly upwelled water that reaches the euphotic zone ensure high surface biological productivity (Fig. 1a) (Naqvi *et al.,* 2006c). In fact, fresh water input to coastal areas off Karnataka (Mangalore) becomes so high that a portion of this part of the Arabian Sea becomes a sink for atmospheric CO_2, a typically unique feature for the Arabian Sea which, as a whole, acts as a global source of CO_2 (Kumar *et al.,* 1996). The ensuing high oxygen demand for respiration of the copious organic matter produced by phytoplankton leads to the development of very intense oxygen deficiency just a few meters beneath the surface. This seasonally-occurring natural suboxic zone occupies an area of about 200,000 km^2 at its peak, and is the largest of its kind in the world (Naqvi *et al.,* 2000, 2006a). As the biogeochemical processes (for example subsurface denitrification) over the western Indian shelf are strongly forced by the SW monsoon, ideally high-resolution paleo-monsoon variability should be traceable through their signatures in form of proxy records stored in sedimentary archives. Important to mention here, seasonal suboxic zone off west coast of India is not contiguous with perennial OMZ of the Arabian Sea which occupies significant portion of slope sediments of the eastern Arabian Sea. Sedimentary records lying under seasonal suboxic zone and perennial OMZ have not been studied in tandem to explore fidelity of conventional geochemical proxies. Another noteworthy point about the eastern Arabian Sea is that, its northern part (off Pakistan and Gujarat) is significantly influenced by winter convective mixing (Madhupratap *et al.,* 1996) and thereby experiences considerable biological productivity in response to NE monsoon. Whereas the Konkan-Goa (KG) coast and areas southward are affected by upwelling and intense precipitation (100-400 $cm.a^{-1}$) during the SW monsoon but do not experience winter convective mixing and hence any significant surface biological productivity during NE monsoon. Detailed hydrography of the eastern Arabian Sea comprising seasonally reversing surface/ subsurface circulation, development of seasonal suboxia and its plausible influence on regional biogeochemistry has been discussed in several detailed reports such as Naqvi *et al.* (2000; 2006a,b), Agnihotri *et al.* (2008a) and Kurian *et al.* (2008).

As said earlier SW monsoon not only manifests itself heavy continental precipitation on the coastal belt of west coast of India (Fig. 2), significant increase in surface biological productivity is also seen (Fig. 1b). Majority of monsoonal proxies employed in this region thereby are actually traces of these monsoonal manifestations *viz.* upwelling induced surface biological productivity, continental runoff in terms of its influence on SST and SSS (sea surface temperature and salinity, respectively). We give brief introductions of all major proxies in following sub-sections. For the first time, we compare subsurface denitrification variability in the eastern Arabian Sea in relation with SW monsoonal intensity variations in both perennial and seasonal suboxic zones of the eastern Arabian Sea. While doing so, we emphasize that volume of chronologically constrained data in both sub-oxic zones is just indicative of inferences made; leaving several questions unanswered demanding many more quality datasets from both oxygen deficient zones.

The other important point which has to be addressed here itself is intricacies involved in achievable temporal resolution in a particular sediment core. Characteristic temporal resolution in a sediment core is mainly governed by (i) Sediment deposition rate and uncertainties involved in the chronologies/ age-depth model used for the sediment core (ii) Sampling interval in commonly employed sampling schemes (cm scale) necessary to yield material enough to analyze different biogeochemical proxies and finally (iii) Analytical uncertainty involved in the measurement of a particular proxy. Some aspects of uncertainties involved in the usually employed ^{14}C chronologies are discussed in another paper by K. Dutta of this very issue. Unfortunately not any significant improvement has come recently to overcome chronological constraints by usually employed methods. However, there have been remarkable advancements in *in-situ* analytical methods. For example, advent of scanning XRF has provided means of determination of sediment core elemental composition at sub-millimeter scale with reasonable accuracy and precision (Agnihotri *et al.,* 2008b).

An overview of proxy indicators used in the eastern Arabian Sea to infer past monsoonal variability

Surface biological productivity:

SW monsoonal upwelling brings subsurface nutrients to euphotic zone of the eastern Arabian Sea and thereby induces copious amount of surface biological productivity (Fig. 1a). Remains of bulk productivity carriers *viz.* C_{org}, N, $CaCO_3$ are expected to be well preserved in sediments depositing beneath both perennial as well as seasonal OMZ due to faster sedimentation rates, better preservation under reducing conditions and minimal bioturbation. The sedimentary C_{org} and N have thus been used quite successfully as proxies of SW monsoon intensity in sediments of the northeastern and eastern Arabian Sea (Schulz *et al.,* 1998; Agnihotri *et al.,* 2002, 2008a). Likewise, sedimentary $CaCO_3$ also has been used as a productivity proxy in the southeastern Arabian Sea (Bhushan *et al.,* 2001; Agnihotri *et al.,* 2003a, b; 2008a). However, following limitations need to be noted with bulk carbonate content usage such as (i) significant contribution can come from relict carbonate deposits and fossil coral reefs in the eastern Arabian Sea (Rao *et al.,* 2003) and/or (ii) post depositional dissolution of $CaCO_3$ under highly suboxic conditions within the sediments might cast doubts on fidelity of this traditional proxy (Bhushan *et al.,* 2001). Availability of biogenic silica (BSi) data, the third major bulk carrier of productivity in the eastern Arabian Sea is too limited to discuss here.

In using remnants of these aforementioned bulk carriers of surface bio-productivity, an inherent limitation is always present i.e. what is the relative proportion of material produced *in-situ* and transported by numerous rivers/ streams by precipitation runoff. Traditionally, source characterization of organic matter has been done using C isotopes ($\delta^{13}C_{org}$) and C/N wt. ratios. Fontugne and Duplessy (1986) reported typical $\delta^{13}C_{org}$ of terrestrial and marine type organic matter of the Arabian Sea as −26 and −20‰ (with respect to PDB). Likewise, mean C/N wt. ratio ranges ~8.0± 2 for typical marine organic matter in this region (Calvert *et al.,* 1995; Bhushan *et al.,* 2001). However, $\delta^{13}C_{org}$ of bed-load sediments of the Mandovi estuary of Goa range from −30.6 and −26.3‰, with an average of −29±1.71‰ (*n*=6) (Rajesh Agnihotri, unpublished data). Several studies carried out in the eastern Arabian Sea even in very shallow marine environment revealed majority of organic matter is typically 'marine' (Bhushan *et al.,* 2001; Agnihotri *et al.,* 2002, 2003, 2008a) despite heavy monsoonal precipitation runoff on the west coast of India.

Subsurface denitrification variations in the eastern Arabian Sea:

Development of intense SW monsoon induced biological productivity leads to consumption of almost all dissolved oxygen resulting in seasonal suboxia (Naqvi *et al.,* 2000). Though water column along the shelf off west coast of India experiences only seasonal suboxia, sediment depositing beneath these waters appear to be strongly reducing throughout at least during the last ~700 years (Agnihotri *et al.,* 2008a). During this period, though surface productivity appears to be varying in tandem with SW monsoonal intensity but subsurface denitrification intensity does not appear to follow same rhythm. Alternatively, sedimentary $\delta^{15}N$, the most reliable and probably only means to measure the extent of past subsurface denitrification in most of the world denitrification zones may not be working in this biogeochemically complex marine realm (Agnihotri *et al.,* 2008a). Contrary to these inferences, in the perennial OMZ region of the eastern Arabian Sea, subsurface denitrification intensity (as measured by sedimentary $\delta^{15}N$) appeared to be varying in concert with surface productivity and hence SW monsoonal intensity on millennial time scale during the Holocene (core 3268G5; Figure 3; Agnihotri et al., 2003a) and same was the case, reported during the late-Quaternary (core MD76-131; Fig. 3; Ganeshram *et al.,* 2000).

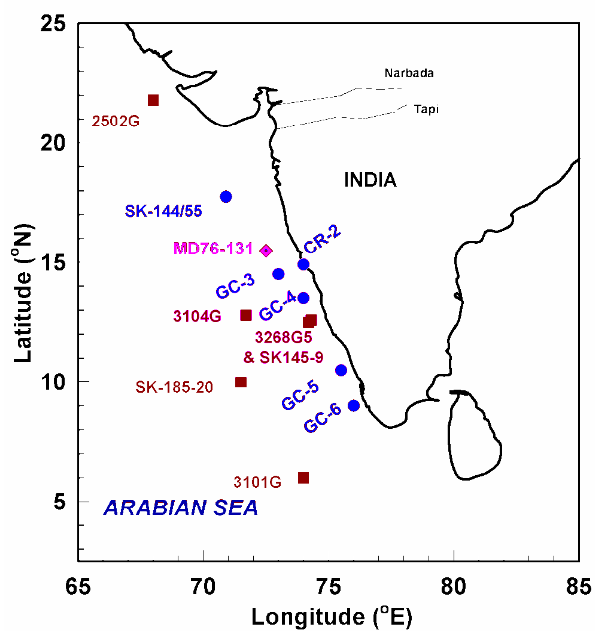


Fig.3: Sediment core locations from the eastern Arabian Sea for reconstructing paleo-monsoonal history on decadal to centennial time scale in different studies carried out in the region so far. Sarkar *et al.,* 1990 (core #185-20); Sarkar *et al.,* 2000 (core #3268G5); Ganeshram *et al.,*2000 (core #MD76-131); Agnihotri *et al.,* 2002 (core #2502G);2003b (3104G & 3101G); 2008a (core #CR2); Thamban *et al.,* 2001 (core #GC-5), 2002 (core #GC-3 & GC-5; 2007(core #148/55); Thamban and Rao, 2001(GC-4 & GC-6); Tiwari *et al.,* 2005a (core #SK145-9); Kurian *et al.,* 2008 (core #CR2).

Molecular biomarkers

Molecular biomarkers have been proposed as more source-specific than bulk proxies *viz.* C_{org}, $CaCO_3$ and biogenic silica. Sterols such as dinosterol and brassicasterol can help in identifying the organisms contributing to overall surface bio-production and its past variability (Volkman *et al.,* 1998; Schulte *et al.*, 1999). Sedimentary concentration of dinosterol, a well established biomarker of dinoflagellates (Boon *et al.,* 1979), and brassicasterol, a marker for diatoms have been linked to primary productivity in the open ocean region of the Arabian Sea (Schubert *et al.,* 1998, Schulte, *et al,* 1999). ß-sitosterol and stigmasterol are major constituents of terrestrial plants (Volkman, 1986; Saliot *et al.,* 1991), and have been used to track the terrestrial organic matter supply in coastal marine environments (Jaffé *et al.,* 2006). However, since they are also produced by marine phytoplankton (Volkman, 1986), the validity of these two sterols as terrestrial markers is not well ascertained (Mudge and Norris, 1997). n-alkanes are also used as a marker of terrestrial organic carbon input to the marine environment as they present in epicuticular waxes synthesized by higher plants (Prahl and Muehlhausen, 1989). Likewise, alkenones (C37 to C39) are produced in the pelagic ocean mainly by two species of organisms (*Emiliania huxleyi* and *Gephyrocapsa oceanica*) belonging to the family Haptophyceae (Volkman *et al.,* 1980). The unsaturation index ($U_{37}^{K'}$) calculated from the concentration of alkenones is used for the reconstruction of paleo- temperature in all over the oceans (*e.g.* Brassell *et al.,* 1986; Prahl and Wakeham, 1987). To check the fidelity of biomarkers, Prahl *et al.* (2000) analyzed sediment trap samples from the central Arabian Sea and showed that they display distinct maxima at the start and stop of the NE and SW monsoons due to rapid change in surface mixing conditions which alter light and nutrient availability, thereby triggering these biomarker signals of export production. Biomarkers have been used to reconstruct changes in paleo-productivity in the eastern and equatorial regions of the Arabian Sea for the last ~300 ka BP and showed enhanced (decreased) productivity during glacial stages (interstadials) (Schubert *et al.,* 1998, Schulte *et al,* 1999). However, certain studies have addressed the issue of degradation of biomarkers during post burial diagenesis, which might affect the reconstruction of past productivity changes (Prahl *et al.,* 2000). Likewise, Sinninghe Damstè *et al.* (2002) showed effect of oxygen exposure time on the preservation of biomarker signals stored in the sedimentary records.

Despite acknowledging the fact that aforementioned biomarkers of productivity also might have some complications/ limitations as studies carried out in other regions, we state that fidelity and potential of these biomarkers in shallow marine environment of eastern Arabian Sea have to be explored in detail, especially during Anthropocene epoch and recent past (Fig. 5). In fact, our recent work Kurian *et al.* (2008) demonstrated first ever application of specific biomarkers (sterols) to reconstruct surface productivity of coastal eastern Arabian Sea for the last 700 years, in conjunction with traditional proxies. Steep increases observed in all the analyzed biomarkers during the Anthropocene (especially last ~50 years) indicate coastal productivity is at its all time maxima (Kurian *et al,* 2008). Delineation of role of anthropogenic forcing in the underlying natural forcing is still needs to be explored with more suitable proxies. Specific biomarkers *viz.* C35/C31 n-alkane ratio and lycopane/ C31 n-alkane ratio could be used as very potential proxies of redox changes (Schulte *et al.,* 1999; Sinninghe Damstè *et al.,* 2003), if used in conjunction with other relatively established inorganic proxies.

Major and trace element abundance

As employed anywhere else in marine realms, several paleo-studies carried out in the eastern Arabian Sea have attempted a suite of major and trace elements for tracking monsoon related processes. For instance, sedimentary abundance of characteristic major and minor elements such as Al, Mg, Ti and also Fe track changes in lithic fraction either by changes in terrestrial runoff/ aeolian inputs (supply) or by just dilution by other biogenic components or both. Fe, although is a redox sensitive element, amount of Fe taking part in redox-changes in continental margin regions is very small compared to its total abundance. Redox conditions in bottom waters/ sedimentary column strongly influence the distribution of some of trace elements such as Mn, Cr, V and U. In sediment pore waters, depending on their oxidation states, these elements have different solubilities. For example, Mn is found to be enriched in sediments from oxic zone, whereas in reducing environment it gets mobilized to pore waters, therefore, gets depleted in solid phase (Bonatti *et al.* 1971; Somayajulu *et al.* 1994; Yadav, 1996). In contrast, Cr, V and U are found to be depleted in oxic zone and enriched in the reducing strata (Dean *et al.* 1997). Thus, an anti-correlation is expected in the depth-profiles between Mn/Al and Cr/Al or V/Al (wt. ratios) during diagenetic changes in sedimentary column.

Sediment cores lying outside the OMZ of the eastern Arabian Sea were found to have much lower abundance of C_{org} and N contents due to much lower sedimentation rates and thereby longer oxygen exposure time at the sediment-water interface, leading to a probable poor preservation of these traditional surface productivity proxies (Agnihotri *et al.,* 2003b). However, elemental ratio of Ba/Al or biogenic Ba content of the sediment has demonstrated its potential to be reliable indicator of surface productivity proxy (Dymond *et al.,* 1992) in these settings (Agnihotri, 2001; Agnihotri *et al.,* 2003b).

C and O isotopes of foraminiferal tests

In addition to aforementioned proxies, most preferred paleoceanographic proxies in the eastern Arabian Sea have been C and O isotopes of surface dwelling foraminifera ($\delta^{13}C$, $\delta^{18}O$) in order to reconstruct evolution of past surface and bottom water hydrographic conditions (Duplessy *et al.,* 1981; Berger *et al.,* 1985; Rostek *et al.,* 1997; Sarkar *et al.,* 1990; Sarkar *et al.,* 2000; Thamban *et al.,* 2001). The $\delta^{18}O$ of foraminiferal calcite is a function of temperature and salinity of the waters in which they grow. Therefore, either a logical way or independent proxy (alkenone derived temperature, for instance) can be used to correct the effect of minor influence from the major one, from the total signal. For example, $\delta^{18}O$ showed a significant positive relationship with surface salinity in the eastern Arabian Sea and hence can be used as proxy indicator to decipher past surface hydrographic conditions, if appropriate temperature corrections are used suitably (Sarkar *et al.* 2000). On the contrary to $\delta^{18}O$, $\delta^{13}C$ of foraminifera reflects productivity of surface waters. Bio-productivity, in general, consume ^{12}C preferentially compared to ^{13}C leaving its signature in form of enriched $\delta^{13}C$ in foraminiferal tests, thereby enabling them to act as proxy for surface productivity.

However, upwelling influences on surface waters have to be considered while interpreting this proxy in terms of surface bio-production.

Using these proxies, Duplessy (1982) showed that the SW monsoon was much weaker during the last glacial maximum (LGM, ~18 ka BP) than present, whereas NE monsoon was much stronger at that time. Sarkar *et al.* (1990) corroborated these findings using oxygen isotope foraminiferal record of sediment core SK-185-20 (Fig. 3) from the southeastern Arabian Sea. Tiwari *et al.* (2005a), however, further constrained the timing of strengthening of NE monsoon by AMS ^{14}C dating as ~19-17 ka BP, based on a sediment core analyzed from equatorial Indian Ocean. Likewise, Thamban *et al.* (2001) derived paleo-monsoonal history from the LGM to present, by measuring oxygen isotope of surface dwelling foraminifera (*G. rubber* and *G. sacculifer)*, geochemical and other sedimentological parameters in a sediment core (GC-5; Fig. 3) from the shelf region of the eastern Arabian Sea. They also applied clay mineral composition and grain size parameters in order to reconstruct the variations in the intensity of summer monsoon precipitation during the late-Quaternary using sediment cores (GC-3 and GC-5; Fig. 3) from the eastern Arabian Sea (Thamban *et al.,* 2002).

Though $\delta^{18}O$ of surface dwelling foraminifera has been regarded as most natural choice for tracking past monsoonal variability, various different external effects such as global ice volume, SST and contribution of local runoff to sea surface salinity require appropriate corrections to retrieve monsoonal (precipitation) signal (Sarkar *et al.,* 2000). Therefore, there is a strong need to go some steps forward involving coupled trace element analyses of foraminiferal tests in addition to oxygen isotopic composition. Trace metals incorporated in the calcium carbonate of foraminiferal shells are becoming increasingly popular for the reconstruction of past environments. Past sea water temperature, carbonate chemistry, nutrient levels and possibly salinity are all reflected by differences in trace metals to calcium ratios. Although it is generally assumed that the incorporation of these trace metals follow thermodynamic relations known from inorganic calcium carbonate precipitation experiments, large offsets have been observed in case of foraminiferal bio-mineralization. The mechanisms responsible for these offsets are, however, poorly known. Exploration of these coupled proxies in search of paleo-monsoon from the eastern Arabian Sea has not yet taken off.

Holocene monsoonal variability from the eastern Arabian Sea on millennial to decadal timescales

We discuss Holocene monsoonal variability here in three time windows (i) millennial scale changes during the entire Holocene (*i.e*. last ~10,000 years), (ii) focusing on centennial to decadal scale variability during the last millennium, in order to understand underlying forcing mechanism(s) and (iii) Anthropocene (last ~100-150 years). Depending on water column hydrography, distance and type of particular continental terrain and most importantly sedimentation rate, suitable locales are chosen for collection of a sediment core for studying a particular time window. For example, outer shelf /slope regions of the eastern Arabian Sea are suitable for studying Holocene epoch on millennial scale as sedimentation rates are typically few cm per thousand years; while inner shelf and locales near to river mouths are capable to yield sedimentation rates typically in range of mm per year. Comparisons were also made between paleo-monsoonal evolution inferred from the eastern Arabian Sea with inferences obtained from northwestern and western Arabian Sea.

Millennial scale Holocene monsoonal variability:

First chronologically well-constrained and temporally well resolved Holocene monsoonal reconstruction was obtained using a sediment core 3268G5 (Fig. 3) raised from heavy precipitation zone of the eastern Arabian Sea (off Mangalore, Figure 2) (Sarkar *et al.,* 2000). Using oxygen isotopes of surface dwelling foraminifera, the parameter P-E index which is the net balance of precipitation over evaporation was used as an index of monsoonal precipitation in the region. Based on its downcore variations, monsoonal intensity was found to have steadily increased from ~10 to ~2 ka BP (Sarkar et *al.* 2000). Surface productivity and sub-surface denitrification intensity, the other manifestations of SW monsoon were also found to be in unison with SW monsoonal intensity during the Holocene (Agnihotri *et al.,* 2003a). Spectral analyses of proxy data from the core 3268G5 also revealed presence of common and significant ~1400 and ~700 year periodicites in the Holocene monsoonal climate coinciding with famous Bond cycles (1400±300 years) observed in north Atlantic proxy records at high latitude (Bond *et al.,* 1997) and the 775-year periodicity observed in the South Asian (Chinese) monsoon (Wang et al., 1999). In a contemporaneous study, Thamban *et al.,* (2001) reconstructed paleo-monsoonal variability for a period since the Last Glacial Maximum (~18-20 ka BP) to present; using oxygen isotope data and other sedimentological parameters from a sediment core from the eastern shelf region of the Arabian Sea. They too found significant oscillations in $\delta^{18}O$ of surface dwelling foraminifera during deglaciation and the Holocene periods suggesting large variations in sea surface hydrography related to monsoonal precipitation, similar to those reported by Sarkar *et al.* (2000). Surface productivity at their core site (shelf region of the southeastern Arabian Sea) appeared to have reduced between ~13 to 6 ka BP, whereas it increased substantially during the last glacial period (~18 to 15 ka BP). They attributed this to enhanced strength of NE monsoon and subsequent convective mixing and nutrient injection (Madhupratap *et al.* 1996), leading to high surface biological productivity. Ganeshram *et al.* (2000) studied one sediment core (MD76-131; Fig. 3) from the eastern Arabian Sea for tracking past surface productivity and sub-surface denitrification variability during the late-Quaternary, but due to very coarser temporal resolution during Holocene, any significant inference can not be made in the present context. In general, not many high resolution paleo-monsoonal records could be generated till then from the slope/ outer shelf region of eastern Arabian Sea owing to relatively slower sedimentation rate resulting in poor temporal resolution and probable bioturbation. Nonetheless, since eastern Arabian Sea is the only locale where from SW monsoon could be reconstructed in terms of precipitation (Fig. 2), with modern advances in new analytical techniques such as scanning XRF in capable of achieving much better temporal resolution than conventional ones (Agnihotri *et al.,* 2008b), it is possible to unravel many *hitherto* aspects of past SW monsoon in Indian context.

In contrast to the precipitation dominated eastern Arabian Sea, upwelling induced surface productivity is supposed to be the best choice to reconstruct past monsoonal variability in the wind dominated western Arabian Sea. Numerous studies from the western Arabian Sea have indeed demonstrated this fact on orbital to millennial timescales. In the present context of Holocene, Gupta *et al.* (2003) measured abundance of *G. bulloides* foraminifera in the core 723A and found a typical decreasing pattern in monsoonal intensity closely following solar (July) insolation at 65° N with conspicuous maxima at ~9-10 ka BP. The observed Holocene monsoonal wind intensity pattern was found to be well supported by continental high resolution stalagmite record (Fleitmann *et al.,* 2003). These studies also find consistency with several other paleomonsoonal reconstructions from the western Arabian Sea which suggested early Holocene period ~8-10 ka BP as most humid interval when monsoon intensity was at its maximum (Sirocko *et al.,* 1996, 2000). Latest Holocene monsoonal record of highest temporal resolution from stalagmite record of Dongee Cave (Wang *et al.* 2005) also supports inferences made by aforementioned studies in the western Arabian Sea.

Therefore, proxy records from the precipitation dominated eastern Arabian Sea (Sarkar *et al.,* 2000; Thamban *et al.,* 2001) appear to be in an obvious contrast with those from western Arabian Sea. Thamban *et al.* (2007) corroborated this fact in their syntheses of results from the entire Arabian Sea where it appears that as a whole, there is no uniform pattern of paleomonsoonal variability during the Holocene in the Arabian Sea. The contrasting Holocene monsoonal patterns between western and eastern Arabian Sea can be possibly understood in terms of gradual southward shift in mean latitudinal position of ITCZ during the Holocene (Fleitmann *et al.,* 2007). A typical pattern of Holocene monsoonal variability inferred from eastern Arabian Sea sediments has been shown schematically in Fig. 4.

It is worth mentioning here that sub-decadally resolved 5000 yr long monsoonal reconstruction has been carried out using varve thickness and other proxy data on a core duplet from the northeastern Arabian Sea (von Rad *et al.,* 1999; Lückge *et al.,* 2001). However, the observed pattern is neither consistent with eastern or the western Arabian Sea trend. As this region is significantly influenced by NW monsoon in addition to SW monsoon, retrieval of the SW monsoonal signal is complicated. This might be a plausible cause responsible for the observed trend of monsoonal intensity in the northeastern part of the Arabian Sea.

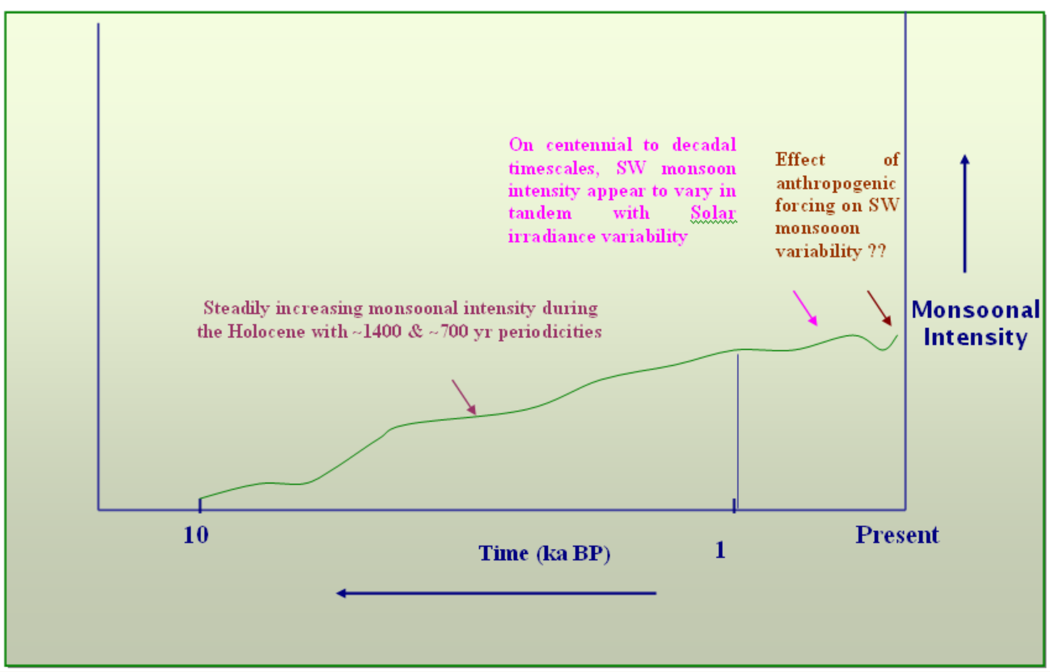


Fig: 4: Schematic presentation of evolution of SW monsoon during the Holocene as inferred from proxy records of the eastern Arabian Sea

Monsoonal variability during the last millennium:

Nature and magnitude of climate variability during the last few millennia with sufficient temporal resolution has received immense interest in paleo-scientists and modelers (Agnihotri *et al.,* 2002, 2008b; Hu *et al.,* 2003; Mangini *et al.,* 2005; Mann, 2007) in order to determine dominant forcing factors, mutual interactions among different climatic components. Since temperature reconstructions for the last two millennia by various workers demonstrated quasi- cyclicity in global temperatures, *i.e.* arrival of warm and cold phases such as medieval warm period (MWP; ~800-1300 AD) and little ice age (LIA; ~1500 to 1900 AD), attempts have been made to understand plausible forcing(s) responsible for this. Various forcing mechanisms were suggested to have influenced global climate on decadal to centennial scale over the last millennium, in which solar irradiance forcing is one of them (Agnihotri *et al.,* 2002). Then, one school of thought believes that extra-tropical changes in north Atlantic were most likely drivers of global climate change, others presume climatic changes occurring at the tropics are likely to be principal drivers of global climate. SW monsoon is one of the major tropical climatic phenomena intimately linked with seasonal migration of inter-tropical convergence zone (ITCZ) across the globe and thereby affecting significant proportion of the world population on inter-annual to decadal timescales. SW monsoon not only impacts billions of human life on Indian sub-continent but also influences significantly hydrography, biology and biogeochemistry of the entire northern Indian Ocean (Arabian Sea and Bay of Bengal). Therefore, a natural thinking developed *i.e.* to study past SW monsoonal history in terms of past changes in hydro-biogeochemistry stored in sedimentary records in form of different proxies arresting signatures of these biochemical changes (Suthhof *et al.,* 2001; Altabet *et al.,* 2002; Agnihotri *et al.,* 2003a; Agnihotri *et al.,* 2008a) and comparing inferences with those made from high latitude climatic changes mainly in north Atlantic (Bond *et al.,* 2001). Several studies (Schulz *et al.,* 1998; Altabet *et al.,* 2002; Gupta *et al.,* 2003; Suthhof *et al.,* 2001) have revealed close connection of monsoonal variability recorded in the Arabian Sea with north Atlantic climate.

Which climatic component responds first to the external forcing and spreads signal across globe is, however, not still known with certainty due to poor age controls. Careful examination of last millennium climate can probably help to a greater extent if generated time series are better chronologically-constrained. Therefore, to investigate synchrony of SW monsoon with global climate various continental and marine archives have to be studied from diverse geographic locations. We discuss here some records from the eastern Arabian Sea spanning last few millennia and compare inferences made with those made from the western Arabian Sea. Agnihotri *et al.* (2002) and Kurian *et al.* (2008) studied sediment cores 2502G and CR-2 from the eastern Arabian Sea, off Saurasthtra (Gujarat) and Goa spanning ~1200 and 700 years respectively (see Fig. 3 for core locations). Outcome of both the studies is common i.e. upwelling induced surface productivity varied in tandem with a common external forcing i.e. solar irradiance variability on decadal to centennial timescales during the last millennium. These studies along with some contemporaneous ones from the western Arabian Sea (Gupta *et al.,* 2005) revealed the fact that solar intrinsic forcing appears to dominate significantly upwelling strength in both western and eastern Arabian Sea and hence monsoonal intensity on decadal to centennial timescale. In a very recent paleoceanographic reconstruction carried out in the Peru margin area (Southern hemisphere) by Agnihotri *et al.* (2008b), it appears that coastal upwelling strength off Peru also shows signatures of a plausible solar irradiance forcing at least during the last two millennia (Agnihotri *et al.,* 2008b) and thus reinforce already made inferences from the eastern and western Arabian Sea. Solar irradiance not only influences coastal upwelling strength in the tropics but also appears to control continental precipitation as well during the instrumental period (Bhattacharyya and Narasimha, 2005). As far as historical background of solar activity on Indian rainfall is concerned, possibly the earliest references on solar forcing of Asian monsoon are Meldrum (1873) and Lockyer (1900).

Since total change in magnitude of solar irradiance forcing on decadal timescale is very minute (0.06-1.0%), it requires amplifying mechanism(s) within the climate system to produce traceable effect. Various physical mechanisms have been proposed to produce this amplification, including alteration of the atmospheric circulation pattern as a result of changes in solar ultraviolet radiation during the solar cycle (Shindell *et al.,* 1999; Haigh, 2001). The exact physical mechanism involved in the observed coupling between solar irradiance changes at the top of the atmosphere and upwelling stimulated surface productivity in the tropics is still not yet clear. However, sensitivity of the mean latitudinal position of ITCZ to solar irradiance changes may be one pathway (Agnihotri *et al.,* 2002 & 2008b; Agnihotri and Dutta, 2003). Stratospheric modulation of upwelling in the equatorial troposphere, which produces a north-south seesaw of convective activity during seasonal migration of ITCZ from northern to southern hemisphere, may be a more acceptable pathway (Kodera, 2004).

Tiwari *et al.* (2005b) measured oxygen isotopes of surface dwelling foraminifera *G. ruber* in a core SK-145-9 (off Mangalore; Fig. 3) and demonstrated that estimated precipitation proxy (P-E) also seem to resonate with solar variability during the last millennium. Thus, by and large, all the high-resolution paleoceanographic studies carried out in the eastern Arabian Sea emphasize a significant role of external solar irradiance forcing on SW monsoon. Upwelling indices broadly vary positively in unison with solar irradiance variability during the last millennium, *i.e.* enhanced surface productivity during all solar maxima and vice versa. Same is the case for coastal rainfall on the west coast of India *i.e.* higher solar activity produces enhanced rainfall and vice versa. From the western Arabian Sea, Anderson *et al.,* (2002) reconstructed monsoonal wind intensity variations using high-resolution upwelling record based on the foraminiferal abundance of *G. bulloides* for the last four centuries. This record is also in general agreement with inferences made from the eastern Arabian Sea *i.e.* suppressed upwelling strength during the LIA and prominent intensification thereafter.

Kurian *et al.* (2008) employed specific biomarkers in the eastern Arabian Sea region to track past surface productivity in conjunction with other conventional proxies like sedimentary C_{org}, N and $CaCO_3$ contents. Among the four measured sterols, Dinosterol, an indicator of dinoflagellate productivity appears to be relatively more sensitive than other proxies to the exerted forcing (Kurian *et al.,* 2008). It is interesting to know that subsurface denitrification intensity in the seasonal suboxic zone off Goa do not appear to be dominantly controlled by surface productivity during the last 700 years (Agnihotri *et al.,* 2008a). This is in an apparent disagreement with concurrent relationship observed between the two during the Holocene in the eastern Arabian Sea, but in the perennial OMZ (off Mangalore) (Agnihotri *et al.,* 2003a).

Monsoonal variability during anthropocene era:

Whether the anthropogenic (greenhouse) forcing has any noticeable influence on the intensity of SW monsoon or not? This is a still vital and open question, not only of scientific importance but also of considerable socioeconomic relevance. Conventionally, it was assumed that with elevated emissions of CO_2 in the atmosphere and increasing temperatures would help plant photosynthesis on land and thereby would cause increased rainfall intensity. In contrast, Goes *et al.* (2005) suggested with increasing global temperatures in response to global warming would reduce high latitude Eurasian ice extent. This would probably reduce land-ocean thermal contrast between Eurasia and Arabian Sea and in turn SW monsoonal strength during the modern Anthropocene epoch. Instrumental (sub-divisional) rainfall data for India do not corroborate suggestions made by Goes *et al.* (2005). However, Goswami *et al.* (2006), based on their detailed analyses of sub-divisional rainfall data suggested that, though there is no discernable influence of global warming/greenhouse forcing on the average rainfall over India, but frequency of extreme events have tremendously increased in recent years. A quantitative delineation between the natural and anthropogenic forcing factors on monsoonal intensity is essential and for that so called 'ultra-high resolution techniques' can play vital role in paleo-monsoonal research. Shallow coastal marine realm of the eastern Arabian Sea again appears to be an in ideal locale for delineation between anthropogenic versus natural forcing factors as precipitation on Konkan-Goa coast showed maximum coherence with Sunspot activity in the instrumental era; and upwelling induced surface productivity indices *e.g.* dinosterol concentration in sediment core CR-2 (Fig. 3) showed appealing covariance with external natural forcing *i.e.* Sunspot acivity (or solar forcing) together with regional continental precipitation in the recent past (Fig. 5).

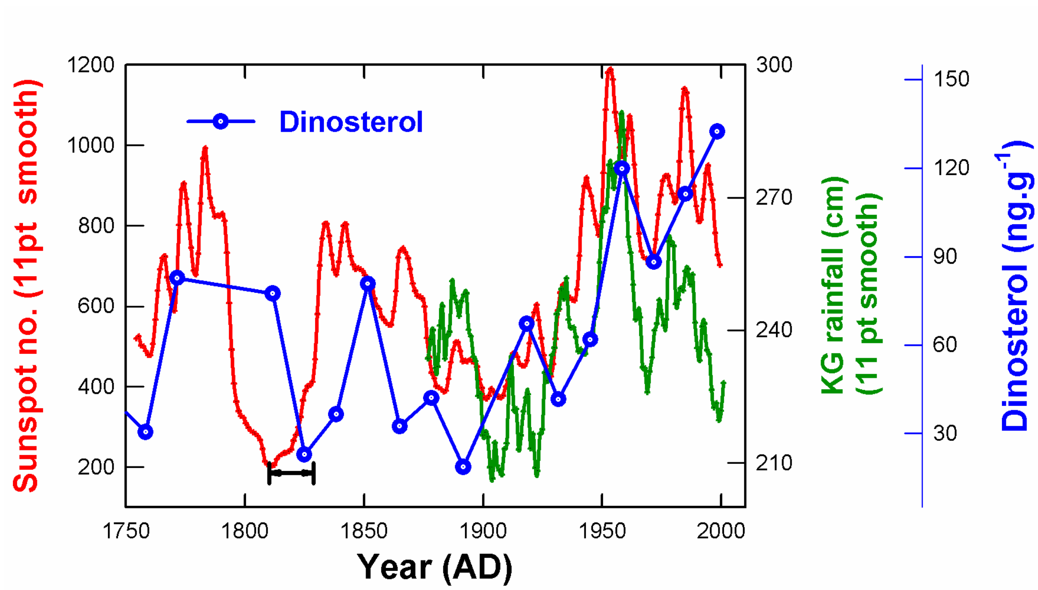


Fig. 5: Covariance observed between monsoonal precipitation on Konkan-Goa coast and surface productivity as mimicked by dinosterol concentration ($ng.g^{-1}$) in sediment core CR-2 in response to external solar forcing (Sunspot activity). Precipitation data for Konkan-Goa coast and Sunspot no. are adapted from websites of Indian Institute of Tropical Meterology (Pune, India) and paleoclimatology site of National climate Data Center (NOAA) respectively. This figure is adapted from Kurian *et al.* (2008)

In the sediment core CR-2 from coastal Goa (Fig. 3, for core-site), steep increases were observed in all the analyzed biomarkers during the Anthropocene (especially last ~50 years) indicating coastal productivity is at its all time maxima (Kurian *et al,* 2008). This unprecedented increase in coastal surface bio-productivity during the last few decades is natural or anthropogenic, could not be characterized with enough certainty. However, this unique increase is not likely to be a preservation artifact as redox sensitive elements distribution in the same core indicates bottom waters/ sediment water interface have remained strongly reducing throughout the deposition period (Agnihotri *et al.* 2008a). Nonetheless, preservation versus supply issue is an important one for applying these new proxies in paleo-monsoonal research and hence should be studied in detail with many more sediment cores in same marine locale with varying sedimentation rates. Both anthropogenic (enhanced supply of fertilizer derived nutrients in coastal waters) and natural (increased Sun's activity in recent decades; Solanki *et al.,* 2004) forcing factors might have resulted in recent increase in surface productivity observed in the coastal zone of the eastern Arabian Sea but their relative role(s) have to be quantified using multi-core-multi-proxy approach.

Concluding remarks

We presented here a comprehensive scenario of Holocene monsoonal history on millennial to decadal time scales revealed by recently studied paleo-records obtained from the precipitation dominated eastern Arabian Sea. Inferences made were also compared with those obtained from the wind dominated western Arabian Sea. Paleo-monsoonal variability in the eastern Arabian Sea exhibits a spatial concordance, however, overall monsoonal variability inferred from the eastern Arabian Sea appears to show a contrasting pattern with respect to that obtained from the western Arabian Sea. A plausible southward shift in mean latitudinal position of ITCZ during the Holocene within the Arabian Sea is a likely interpretation for this anomaly (Fleitmann *et al.,* 2007). However, this anomaly underlines the importance of the eastern Arabian Sea region as a suitable paleoceanographic locale for reconstruction of past monsoon in terms of precipitation.

In contrast to millennial scale variability of monsoon during the Holocene, past monsoonal variability on centennial to decadal time scale at least during the last few millennia, appears to be significantly influenced by external solar irradiance forcing in the entire Arabian Sea. Therefore, solar forcing can be treated as the most dominant natural forcing for the variability of SW monsoon in the pre-anthropogenic era. The eastern Arabian Sea also presents itself as an ideal locale for calibration of various monsoonal proxies with instrumental rainfall data in the rapidly depositing shelf sediments under seasonally suboxic waters. Chronologies of sediments can be improvised by compound specific dating schemes using new accelerator mass spectrometer (AMS) technique available in India (Institute of Physics, Bhubaneswar). Future paleoceanographic research should focus on a quantitative assessment of anthropogenic forcing which is most likely riding over natural forcing component of monsoonal variability.

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