

Link between Western Arabian Sea Surface Temperature and Summer Monsoon Strength and High-Latitude Abrupt Climate Events

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Abstract: Sea surface temperature (SST) is modulated by the summer monsoon winds and the associated upwelling in the Arabian Sea. Here, I report the changes of summer and winter SST's in the western Arabian Sea reconstructed for the last 22 ka using Artificial Neural Networks (ANN's) based on quantitative analyses of planktic foraminifera. High seasonal SST contrast between winter and summer during the last glacial period indicates weak upwelling and strong cold northeasterly winds. Minimum seasonal SST contrast during the Holocene reflects strong upwelling. Contrast between summer and winter SST's documented here is in agreement with the other upwelling proxies recorded in the Arabian Sea sediments over the time span covered in the present study. This suggests that seasonal SST is a potential proxy to quantify the upwelling and the associated monsoon strength in the Arabian Sea. During an intense phase of monsoon in the Early Holocene a drastic reduction of annual summer and winter SST's is documented around 8.2 cal ka, which coincides with a decline of the monsoon upwelling strength. A similar cooling event around 8.2 cal ka was recognized in the north Atlantic as well as in the tropics. This suggests a link between high-latitude climate on the one hand and monsoon upwelling strength in the Arabian Sea and tropical climate changes on the other.

Keywords: Indian Ocean, Arabian Sea, Monsoon, Abrupt climate events, Sea surface temperature, Artificial neural networks.

INTRODUCTION

Biogeochemical cycling processes in the Arabian Sea are controlled by both the southwest (SW) and northeast (NE) monsoon wind systems of the summer and winter seasons respectively. The integrated history of plankton blooms is preserved as distinct plankton fossil assemblages in sediment facets, forming a continuous geologic record of these processes in the upper ocean. Numerous proxies from marine and continental records have been used to study the changes of monsoon variability and to understand the forcing mechanisms of the Asian summer monsoon covering a time span of thousands of years (Clemens et al. 1991; Prell et al. 1992; Sirocko et al. 1993; Naidu and Malmgren, 1996; Schulz et al, 1995; Gupta et al. 2003). Proxy indicators, by virtue of their physical, biological and chemical origins, are indirectly related to paleoceanographic and paleoclimatic variables of interest. Therefore, no single proxy has a unique and direct association with monsoon strength. All proxies have the potential to be influenced by processes other than changes in the monsoon or climatic and/or oceanographic variables of direct interest (Clemens and Prell, 2003). Hence, a multi-proxy approach, which

relies on the evaluation of a number of independent proxies for a given variable, appears to be good to study the variability of monsoon strength.

The heat flux from the Arabian Sea to the atmosphere is higher during winter (November, December and January) compared to other months (Hastenrath and Lamb, 1979). During the SW monsoon the western Arabian Sea gains heat whereas the eastern Arabian Sea loses heat to the atmosphere. Modern Sea Surface Temperature (SST) varies from 23.2 to 28.4 °C at the location of ODP Site 723A. Minimum SST during July through September (SW monsoon season) and maximum SST during inter-monsoon are documented (Fig. 1). Summer SST's are lower than winter SST's along the Oman Margin due to strong upwelling. In other words, seasonal SST changes would reflect the intensity of upwelling in this region. Attempts have been made to trace the upwelling strength based on the SST difference between glacial and interglacials derived mainly from oxygen isotope and alkenone data (Zahn and Pederson, 1991; Emeis et al. 1995). These studies did not document any systematic relationship between SST changes and upwelling strength on glacial and interglacial

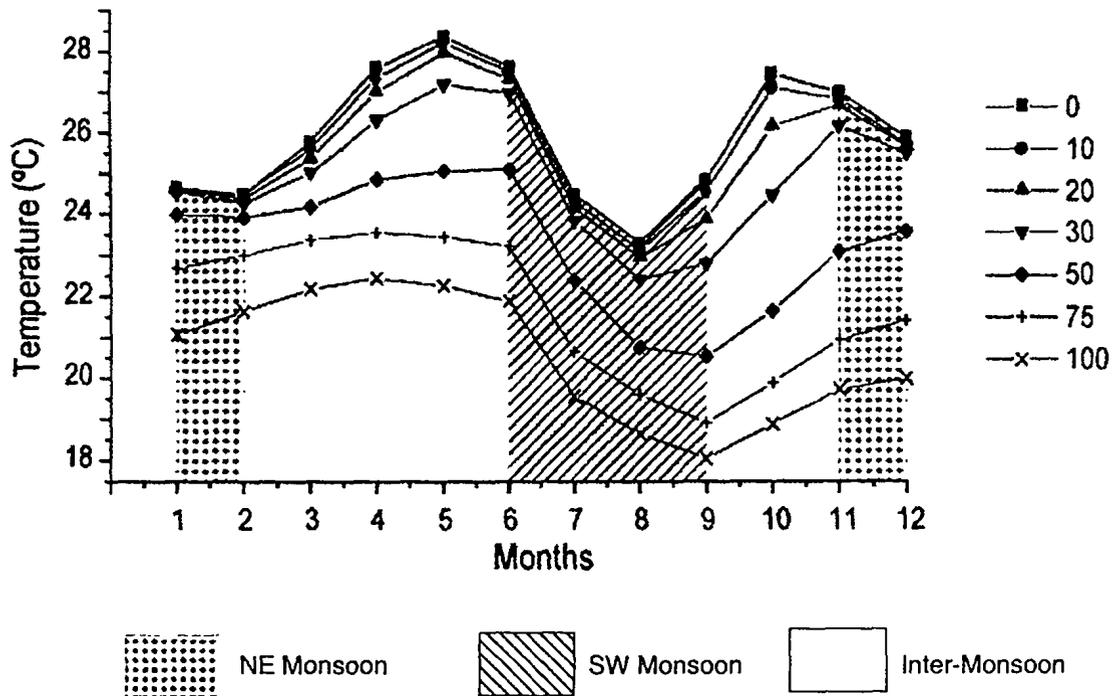


Fig. 1. Annual temperature variation at ODP Site 723 from 10,20,30,50, 75 and 100 m water depths. Temperature data are from Levitus (1982).

time scales, because they dealt with annual, rather than seasonal, SST's. Here, I discuss the seasonal SST changes over the last 22 ka at the Ocean Drilling Program (ODP) Site 723A, to i) know how the seasonal SST changed through time in response to S W monsoon upwelling, and ii) evaluate the relationships between high-latitude abrupt climate events and SST changes in the western Arabian Sea.

Hydrography

Seasonal reversal of the monsoon winds over the Arabian Sea influences surface circulation, productivity, biogenic and lithogenic fluxes, CO₂ uptake and heat budget in the region. The SW monsoon is accompanied by strong winds (~30 knots), cloudy skies and moist air. In addition, the ocean gains heat (an average of 9.5 Wm⁻²), but SST decreases by 5.5 °C and the mixed layer deepens to almost 80 m in the central Arabian Sea and becomes shallow at the Oman Margin compared to the inter monsoon seasons (Schott and McCreary, 2001). The salinity in the upper water column during the S W monsoon is reasonably uniform, but decreases from about 36.5 to 36.0 ‰ during the course of the SW monsoon season. The SW monsoon wind field causes upwelling along the Arabian coast, leading to persistent jets of cold upwelled water extending from the Oman coast and often advecting laterally about 600 km offshore (Brink

et al. 1998; Fischer et al. 2002). Outside of the regions of coastal upwelling during the SW monsoon, SST's are generally high, varying from 27 to 29 °C. The NE monsoon is characterized by moderate winds (~10 knots), clear skies and dry air. During the NE monsoon the ocean loses heat (an average of 19.7 Wm⁻²) to the atmosphere with a 3 °C SST decrease (Weller et al. 2002). The two intermonsoon seasons are substantially different from either of the monsoon seasons. These are characterized by weak winds and strong sea-surface heating. The SW monsoon determines the climate of the northern Indian Ocean during the northern hemisphere summer and the NE monsoon the climate of the northern Indian Ocean during the northern hemisphere winter. The winds are generally weak during the intermonsoonal periods, with the Fall intermonsoon being significantly shorter than the Spring intermonsoon (Weller et al. 2002).

METHODS

Site 723A is located in the intense upwelling area along the western Arabian Sea (18°03'N; 57°37'E) at a water depth of 808 m. The upper 7.4 m of the core was sampled at 10 cm interval, which gives a time resolution of ~250 years. The geochronological control of the core is based on

AMS ^{14}C dates (Naidu and Malmgren, 2005). The past annual, summer and winter season SST's were estimated using Artificial Neural Networks (ANN's). The general principles and architecture of a back propagation neural networks are described by Malmgren and Nordlund (1996). Artificial neural networks were trained on the planktonic foraminiferal census of 361 core-tops from the Indian Ocean. The training set consisted of 271 samples (75 %) and the test set of the remaining 90 samples (25 %). The training process was repeated 10 times to obtain a reliable estimate of the precision of the predictions of the test set observations. The average precision for the summer and winter SST's are in the range of 0.82 to 1.19 °C. More details on the computations of neural networks are given by Naidu and Malmgren (2005).

RESULTS AND DISCUSSION

Seasonal Temperature Contrast

Sea surface temperatures (SST's) along the western Arabian Sea are highly influenced by upwelling. The difference between summer and winter SST's is strongly dependent on the strength of the SW monsoon winds and the associated upwelling. Therefore, summer and winter SST contrast would explain the variability of upwelling and the SW monsoon wind strength in the past. In other words, higher and lower seasonal SST contrasts indicate weaker and stronger upwelling strength at this site. Reconstructed SST's for winter and summer show that the seasonal contrast was moderate from 22 to 18 cal ka, the highest between 18 and 14 cal ka and minimum throughout the Holocene (Fig. 2). This suggests that in general summer monsoon-driven upwelling was weaker in the last glacial period than in the Holocene, which is in agreement with other

upwelling proxies used in the western Arabian Sea (Prell, 1984; Naidu and Malmgren, 1996; Overpeck et al. 1996). Seasonal SST contrast was slightly higher during the Younger Dryas Event (~12 cal ka) compared to the rest of the Holocene. Therefore, it is tempting to suggest that the summer monsoon wind strength and the associated upwelling were weaker during the Younger Dryas. In addition, the seasonal SST contrast record shows abrupt events within the last glacial period compared to the Holocene. These abrupt high-amplitude fluctuations are mainly related to changes in winter SST (Fig. 2). This could be due to the larger air-sea temperature difference during the last glacial period, which aids in cooling the sea surface to a larger extent through direct sensible heat loss from the ocean to the atmosphere. Such air-sea interactions were highly unstable during the last glacial period. This winter surface-water cooling extended up to the Arabian coast during the last glacial period, in contrast to the present-day winter cooling which is restricted to the NE region of the Arabian Sea.

Seasonal SST Contrasts Between the Eastern and Western Arabian Sea

Modern SST's are higher in the eastern Arabian Sea compared to the western Arabian Sea (Levitus, 1982). Seasonal SST contrasts between winter and summer are slightly higher in the eastern Arabian Sea (-0.44 °C) than in the western Arabian Sea (~-0.15 °C) (Levitus, 1982). Southwest monsoon upwelling considerably lowers the summer SST in the western Arabian Sea, which causes a low seasonal SST contrast between summer and winter. The modern SST, obtained from alkenone data for core-tops, also is lower in the western Arabian Sea compared to the eastern Arabian Sea (Table 1). This is analogous to the

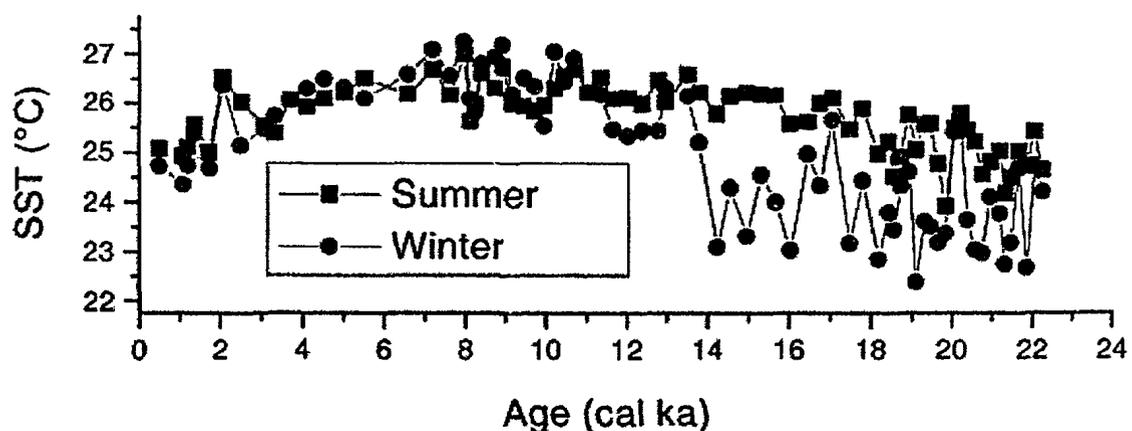


Fig. 2. Sea-surface temperature contrast between summer and winter seasons at ODP Site 723A, Western Arabian Sea.

Table 1. Modern and LGM SST's (°C) for the western and eastern Arabian Sea. Estimates of SST are based on the unsaturation index (Uk37) (Sonzogni et al. 1998)

Western Arabian Sea			Eastern Arabian Sea		
Core No.	Modern	LGM	Core No.	Modern	LGM
MD77203	25.2	22.6	MD77195	27.5	25.2
MD77202	26.0	23.1	MD77194	27.3	25.8
ODP723	25.4	23.4	MD77191	27.5	25.8
TY93929	26.0	24.4	MD76131	27.5	25.2
			MD90963	28.0	25.5

modern SST data for these regions. Despite weak upwelling during the Last Glacial Maxima (LGM), SST's are lower in the western Arabian Sea than in the eastern part (Table 1). Several studies suggested a greater influence of the NE monsoon during the LGM along the eastern Arabian Sea (Duplessy, 1982; Cayre and Bard, 1999). It is argued here that if the NE monsoon wind effect was more severe in the eastern Arabian Sea during the LGM, one would expect lower SST's here than in the western Arabian Sea. However, such a pattern of SST is not recorded during the LGM between the eastern and western Arabian Sea. This suggests that the NE monsoon winds were stronger in the entire Arabian Sea during the LGM and further that the influence of the dry, cold NE monsoon winds extended up to the Oman Margin during the last glacial period.

Seasonal SST Contrast and Inter Tropical Convergence Zone (ITCZ)

The precession cycle of the Earth's orbit determines the strength of monsoon winds and variation in seasonality (Clemens and Prell, 2003). Precession of the Equinox changes the Earth-Sun distance and the season such that over a period of approximately 21 ka, summer migrates through perihelion to aphelion. The Sun-Earth distance determines the solar radiation received by the Earth in a particular season. The position of the Inter Tropical Convergence Zone (ITCZ) is strongly dependent on seasonal changes of solar radiation. The ^{18}O record of speleothem calcite from the Qunf Cave reflects the changes in precipitation rates. More negative ^{18}O values result from an increase in precipitation when the ITCZ is overhead. When the ITCZ moves south, precipitation decreases and the ^{18}O values become more positive (Fleitmann et al. 2003). Therefore, seasonal migration of the ITCZ determines the amount of precipitation over the Indian subcontinent.

The relatively higher seasonal SST contrast between 3 ka of the Late Holocene and the Early Holocene is attributed to the weak summer monsoon winds due to the

shift of ITCZ further south. Changes in the position of ITCZ during the Holocene are also documented in the sedimentary record of the Cariaco Basin off the coast of northern Venezuela (Haug et al. 2001). The general southward shift of the ITCZ during the Holocene may have resulted from changes in the seasonality of insolation associated with the 21 ka precession component of Milankovitch forcing. During the Late Holocene, the southern hemisphere insolation became more seasonal and the northern hemisphere insolation less seasonal (Berger and Loutre, 1991). This should have decreased the capacity of the northern summer insolation maximum to pull the ITCZ off the equator while increasing the insolation to the south, reducing the strength of summer monsoon winds as evident from the seasonal SST records from the Arabian Sea. Thus, the interplay between the precessional cycle and solar insolation changes determines the strength of the summer monsoon winds and the associated rainfall. Recent evidence from Chinese speleotherm records also suggest a strong link between solar activity and monsoon (Wang et al. 2005). Therefore, seasonal SST's of the Arabian Sea are also highly dependent on the precessional cycle.

Monsoon Upwelling Response to the 8.2 cal ka Cold Event

An Early Holocene cold pulse with an amplitude of about one half that of the Younger Dryas cold event has been documented in the oxygen isotope records from Greenland ice cores (Alley et al. 1997). This event, commonly referred to as the "8.2 cal ka event", has been reported from many sites around the North Atlantic Ocean (Klitgaard-Kristensen et al. 1998; von Grafenstein et al. 1998; Tinner and Lotter, 2001), and the Labrador Sea (Barber et al. 1999). The monsoon upwelling indices show a strengthening phase of monsoon starting around 14 cal ka. Although the SW monsoon winds were strong from 9 to 6 cal ka (Naidu and Malmgren, 1996), around 8.2 cal ka the strength of upwelling strikingly decreased (Fig. 3). One could argue that the decrease in upwelling strength around 8.2 cal ka would cause an increase in summer SST. The severe winter cooling would compensate the increase in summer SST due to weak upwelling around 8.2 cal ka and thus a net cooling is documented in the summer SST data. Further during this period the annual, summer and winter SST's also abruptly dropped suggesting that this event was a response to the atmospheric forcing of climate change in this part of the globe. The ^{18}O values of speleothem calcite from Oman and China also show a decrease of monsoon rainfall during the 8.2 cal ka event (Neff et al. 2001; Wang et al. 2005). Similarly, speleothem isotopic record of Costa Rica

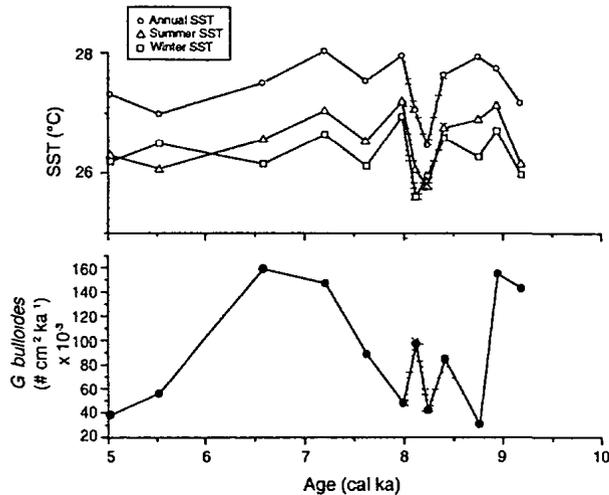


Fig. 3. Flux of *Globigerina bulloides* and annual, summer and winter sea-surface temperature changes over the last 10 cal ka. The response of decrease in monsoon upwelling to the 8.2 ka cold event is highlighted.

also indicates a weakened Early Holocene monsoon in response to the 8.2 cal ka event. All these lines of evidence strongly suggest that rainfall in the tropics responded to the 8.2 cal ka cold event that was first recorded in the North Atlantic. This cold event signal may have propagated to the tropics through atmospheric circulation. This tropical dry, cold event at 8.2 cal ka suggests a tropical-extratropical teleconnection, i.e., a possible association of the Indian monsoon rainfall with high-latitude climate changes.

Relationship Between Abrupt High-latitude Climate Events and Summer Monsoon

Linking the climatic events of the high latitudes with those of the tropics in general and with the Asian monsoon in particular gained much importance during the past decade. A synchronicity has been demonstrated between changes of monsoon intensity and variations of temperature in Greenland Ice Cores and the North Atlantic (Sirocko et al. 1993, Schulz et al. 1998, Altabet et al. 2002, Gupta et al. 2003). Are these casual coincidences or physical mechanisms that explain a link between high-latitude climate changes and the monsoons? None of these studies, however, has shown an influence of SST changes in the North Atlantic on tropical latitudes and the Indian monsoon system. However, the flickering behavior of the northern hemisphere high-latitude climate has been explained by invoking changes in the thermohaline circulation of the deep ocean, affecting the transport of warm subtropical waters to the North Atlantic (Broecker, 1997). Climate models have supported this concept and the

important role of the North Atlantic SST for the temperature of Europe and northern Asia (deMenocal and Rind, 1993). It has been proposed that the Pacific El Niño is capable of affecting even the remotest parts of the globe, and that the Asian monsoon and the Pacific El Niño are coupled systems (Webster et al. 1998). Such low- and high-latitude teleconnections could be mediated through the jet stream of the upper troposphere and lower stratosphere, which encompasses the entire globe. A close connection between the jet stream and ENSO is documented (Bjerknes, 1969). Therefore, during strong El Niño years warm tropics affect the duration, position and strength of the jet stream teleconnecting atmospheric signals all over the globe within weeks/months.

Sea surface temperatures of the Arabian Sea are controlled by the summer monsoon upwelling driven by the SW monsoon winds. Thus, lower summer SST's are due to strong upwelling and vice versa. Increase in % hematite-stained grains reflects cold climate in the North Atlantic due to the advection of cooler, ice-bearing surface waters eastward of the Labrador Sea and southward of the Nordic Seas (Bond et al. 2001). Here, I have compared the % hematite-stained grains with the summer sea surface temperature (Fig. 4) to explore the possibility of a link between the North Atlantic cold events and summer SST.

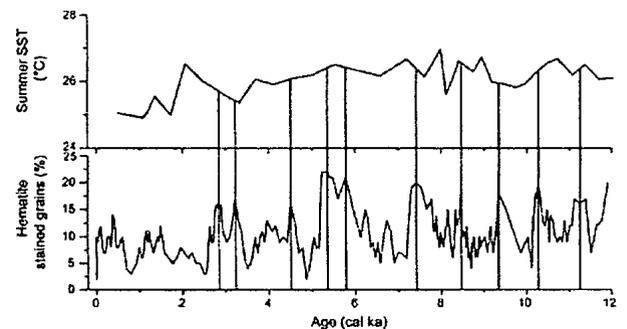


Fig. 4. Profiles of summer sea surface temperature at ODP Site 723 A and % hematite stained grains during the Holocene in core MC52-VM29-191 from the North Atlantic. Hematite-stained grain data from Bond et al. (2001).

in the Arabian Sea. Peaks of % hematite stained grains correspond to lower as well as higher summer SST's, suggesting an inconsistency between the two records. The inconsistency could be due to 1) the difference in sampling resolution between the two records, and/or 11) summer SST's not being linearly related to the temperature changes of the North Atlantic.

It is not clear whether the Indian monsoon variability is driven by the North Atlantic climatic changes or El Niño.

oscillations of the Pacific. Therefore, more attention should be paid in the years to come to determine whether or not the monsoon changes are linked to any of these events or monsoon changes themselves could trigger changes in the North Atlantic climate or El Niño events.

SUMMARY

Sea surface temperatures (SST's) of the western Arabian Sea are strongly modulated by the strength of the SW monsoon winds. Reconstructed summer and winter SST's were used to discuss the variability of the SW monsoon wind strength and the associated upwelling. The following important points emerged:

- 1 Seasonal SST difference between summer and winter seasons is directly related to the upwelling intensity in the western Arabian Sea. Higher and lower seasonal SST differences are noticed during the last glacial period and the Holocene respectively, reflecting weak and strong upwelling during the last glacial period and the Holocene respectively. In addition, the seasonal SST record shows a more refined picture of the changes in upwelling pinpointing the abrupt upwelling events during the Holocene.
- 2 A comparison of SST changes between the eastern and western Arabian Sea suggests the prevalence of strong NE winds over the entire Arabian Sea during the LGM and the influence of dry, cold NE monsoon winds up to the Oman Margin during the last glacial period.
- 3 Annual, summer and winter SST's show an abrupt cooling around 8.2 cal ka, which corresponds to the widely documented cold event in Greenland and the North Atlantic Ocean. The upwelling indice record shows a drastic reduction of upwelling strength around 8.2 cal ka, suggesting a link between high-latitude cooling and the Indian monsoon.

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References

- ALLEY, R. B., MAYEWSKI, P. A., SOWERS, T., STUIVER, M., TAYLOR, K. C. and KLARK, P. U. (1997) Holocene climatic stability: a prominent wide spread event 8200 yr ago. *Geology*, v25, pp 483-486
- ALTABET, M. A., HIGGINSON, M. J. and MURRAY, D. W. (2002) The effect of millennial-scale changes in Arabian Sea denitrification on atmospheric CO₂. *Nature*, v 415, pp 159-162
- BARBER, D. C., DYKE, A., HILLAIRE-MARCEL, C., JENNINGS, A. E., ANDREWS, J. T., KERWIN, M. W., BILODEAN, G., MCNLDY, R., SOUTON, J., MOREHEAD, M. D. and GAGNON, J. M. (1999) Forcing of the cold event of 8200 years ago by catastrophic drainage of Laurentide lakes. *Nature*, v400, pp 344-348
- BORG, A. and LOUÏRE, M. F. (1991) Insolation values of the climate of the last 10 million years. *Quat. Sci. Rev.* v 10, pp 297-317
- BJERKNES, J. (1969) A possible response of the atmospheric Hadley circulation to equatorial anomalies of ocean temperature. *Tellus*, v 18, pp 820-829
- BOND, G., KROMER, B., BEER, J., MUSCHELER, R., EVANS, M. N., SHOWERS, W., HOFFMAN, S., LOTTI-BOND, R., HAJDAS, I. and BONANI, G. (2001) Persistent Solar Influence on North Atlantic Climate during the Holocene. *Science*, v 294, pp 2130-2136
- BRINK, K. R., ARNONE, P., COBLE, C., FLAGG, B., JONES, J., KINDLE, C., LEE, D., PHINNEY, M., WOOD, YENTSCH and YOUNG, D. (1998) Monsoons boost biological productivity in Arabian Sea. *EOS, Trans. Amer. Geophys. Union*, v27, pp 168-169
- BROECKER, W. S. (1997) Thermohaline circulation, the Achilles Heel of our climate system: will man made CO₂ upset the current balance? *Science*, v 278, pp 1582-1888
- CAYRE, O. and BARD, E. (1999) Planktonic foraminiferal and alkenone records of the last deglaciation from the eastern Arabian Sea. *Quat. Res.*, v 52, pp 337-342
- CIEMENS, S., PREIL, W. L., MURRAY, D. G., SHIMMIELD, G. B. and WEEDON, G. (1991) Forcing mechanisms of the Indian Ocean Monsoon. *Nature*, v 353, pp 720-725
- CLEMENS, S. and PRELL, W. L. (2003) A 350,000 year summer monsoon multi-proxy stack from the Owen Ridge, Northern Arabian Sea. *Mar. Geo.* v 201, pp 35-51
- DEMENOCAL, P. B. and RIND, D. (1993) Sensitivity of Asian and African climate to variations in seasonal insolation, glacial ice cover, sea surface temperature, and Asian Orography. *Jour. Geophys. Res.*, v98, pp 7265-7287
- DUPLESSY, J. C. (1982) Glacial to interglacial contrasts in the northern Indian Ocean. *Nature*, v 295, pp 494-497
- EMEIS, K. C., ANDERSON, D. M., KROON, D. and SCHULZ-BULL, D. (1995) Sea-surface temperatures and history of monsoon upwelling in the Northwestern Arabian Sea during the last 500,000 years. *Quat. Res.*, v43, pp 355-361
- FISCHER, A. F., WELLER, R., RUDNICK, A. D. L., ERIKSEN, C., LEE,

- C , BRINK, M K , Fox, C A and LEBEN, R R (2002) Mesoscale eddies, coastal upwelling, and the upper-ocean heat budget in the Arabian Sea *Deep-Sea Res II*, v49, pp 2231-2264
- FLE MANN, D, BURNS, S J , MUDELSEE, M , NEFF, U , KRAMERS, J , MANGINI, A and MATTLER, A (2003) Holocene Forcing of the Indian Monsoon Recorded in a Stalagmite from Southern Oman *Science*, v 300, pp 1737-1739
- GUPTA, A K , ANDERSON, D M and OVERPECK, J T (2003) Abrupt changes in the Asian southwest monsoon during the Holocene and their links to the North Atlantic Ocean *Nature*, v421, pp 354-356
- HASTENRATH, S and LAMB, P J (1979) *Climatic Atlas of the Indian Ocean Part 1, Surface Circulation and Climate* University of Wisconsin Press, Madison, p 97
- HAUG, G H , HUGHEN, K A , SIGMAN, D M , PETERSON, L C and ROHL, U (2001) Southward Migration of the Intertropical Convergence Zone through the Holocene *Science*, v293, pp 1304-1308
- KLITGAARD-KRISTENSEN, D , SEJRUP, H P, HAFLIDASON, H , JOHNSEN, S and SPURK, M (1998) A regional 8200 cal yr BP cooling event in northwest Europe, induced by final stages of the Laurentide ice-sheet deglaciation? *Jour Quat Sci*, v 13, pp 165-169
- LEVITUS, S (1982) *Climatological atlas of the world ocean* National Oceanic and Atmospheric Administration Professional Paper 13, Rockville, Maryland, 173p
- MALMGRLN, B A and NORDLUND, U (1996) Application of artificial neural networks to chemostratigraphy *Paleoceanography*, v 11, pp 505-512
- NAIDU, PD and MAI MGREN, B A (1996) A high-resolution record of late Quaternary upwelling along the Oman Margin, Arabian Sea based on planktonic foraminifera *Paleoceanography*, v 11, pp 129-140
- NAIDU, PD and MAI MGREN, B A (2005) Seasonal sea surface temperature contrast between the Holocene and Last Glacial Period in the western Arabian Sea (ODP Site 723A) Modulated by monsoon upwelling *Paleoceanography*, v 20(1), PA100410 1029/2004PA001078
- NLFP, U , BURNS, S J , MANGINI, A , MUDELSEFF, M , FLEITMANN, D and MATTLER, A (2001) Strong coherence between solar variability and the monsoon in Oman between 9 and 6 kyr ago *Nature*, v 411, pp 290-293
- OVERPECK, J , ANDERSON, D , TRUMBORE, S and PRELL, W L (1996) The southwest Indian Monsoon over the last 18,000 years *Clim Dyn*, v 12, pp213-225
- PRELL, W L (1984) Variation of monsoonal upwelling A response to changing solar radiation *In* J E Hansen And T Takahashi (Eds), *Climate Processes and Climate Sensitivity Geophys Mono Ser, AGU, Washington, D C v 19, pp48-57*
- PRELL, W L , MURRAY, D W, CLEMENS, S and ANDERSON, D M (1992) Evolution and variability of the Indian Ocean Summer Monsoon Evidence from western Arabian Sea Drilling Program *Geophys Monogr, AGU, Washington, D C*, v 70, pp 447-469
- SCHOTT, F A and MCCREARY J P (2001) The monsoon circulation of the Indian Ocean *Progress in Oceanography*, v 51, pp 1-123
- SIROCKO, F, SARNTHEIN, M , ERLLENKEUSER, H , LANGE, H , ARNOLD, M and DUPLESSY, J C (1993) Century scale events in monsoon climate over the past 24,000 years *Nature*, v 364, pp 322-324
- SCHDLZ, H , VON RAD U and ERLLENKEUSFR, H (1998) Correlation between Arabian Sea and Greenland climate oscillations of the past 110, 000 years *Nature*, v 393, pp 54-57
- SONZOGNI, C , BARD, E and ROSTEK, F (1998) Tropical sea-surface temperatures during the last glacial period A view based on alkenones in Indian Ocean Sediments *Quat Sci Rev*, v 17, pp 1185-1201
- TINNER, W and LOTTER, A (2001) Central European vegetation response to abrupt climate change at 8.2 ka *Geology*, v29, pp 551-554
- VON GRAFENSTEIN, U , ERLLENKEUSER, H , MULLER, J , JOUZEL, J and JOHNSEN, S (1998) The cold event 8,200 years ago documented in oxygen isotope records of precipitation in Europe and Greenland *Clim Dyn*, v 14, pp 73-81
- WANG, Y, CHENG, H , EDWARDS, R L, Hr, Y, KONG, X , AN, Z , Wu, J , KELLY, M J , DYKOSKI, C A and Li, X (2005) The Holocene Asian Monsoon Links to Solar Changes and North Atlantic Climate *Science*, v 308, pp 854-857
- WEBST R, P J , M GANA, V O , PALMER, T N , SHUKLA, J , TOMAS, R A. YANAI, M and YASUNARI, T (1998) Monsoons processes, predictability, and the prospects for prediction *Jour Geophys Res*, v 103, pp 14451-14510
- WLL R, R A , FISCHER, A S , RUDNICK, D L , ERIKSEN, C C , DICKEY, T D , MARRA, J , Fox, C and L BEN, R (2002) Moored observations of upper-ocean response to the monsoons in the Arabian Sea during 1994-1995, *Deep-Sea Res II*, v49, pp 2195-2230
- ZAHN, R and PLDFRSON, T F (1991) Late Pleistocene evolution of surface and mid depth hydrography at the Oman Margin planktonic and benthic isotope records at Sue 724 *Proc Ocean Drilling Program, Scientific Results*, v 117, pp 291-308