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# Indian Summer Monsoon Variability during the Holocene as Recorded in Sediments of the Arabian Sea: Timing and Implications

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**Indian monsoon precipitation fluctuated significantly during the Holocene and a reliable reconstruction of the timing of the events and their implications is of great benefit to our understanding of the effect and response of low latitude climate systems to the forcing factors. We have carried out high-resolution terrigenous proxy studies on a laminated sediment core from the Oxygen Minimum Zone of the eastern Arabian Sea margin to reconstruct the summer monsoon-controlled precipitation changes during the Holocene. The temporal variation in the terrigenous proxy indicators of this core, in combination with other high-quality cores from the Arabian Sea, suggests several abrupt events in monsoon precipitation throughout the Holocene. The early Holocene monsoon intensification occurred in two abrupt steps at 9500 and 9100 years BP and weakened gradually thereafter, starting at 8500 years BP. A weakening in precipitation recorded at ~7000 years BP, synchronous with similar conditions in India. One of the most significant weak monsoon periods recorded in our studies lies between 6000 and 5500 years BP. Spectral analysis of the precipitation records reveals statistically significant periodicities at 2200, 1350, 950, 750, 470, 320, 220, 156, 126, 113, 104 and 92 years. Most of these millennial-to-centennial cycles exist in various monsoon records as well as the tree ring $\Delta^{14}$C data and/or other solar proxy records. We suggest that throughout the Holocene, externally, small changes in solar activity controlled the Indian monsoon to a large extent, whereas internally, non-solar causes could have influenced the amplitude of decadal-to-centennial oscillations.**

Keywords:
· Holocene,
· Indian monsoon,
· Arabian Sea,
· climate variability,
· solar forcing.

## 1. Introduction

The climate fluctuations in the Indian subcontinent are fundamentally related to the dynamics of the seasonally reversing monsoon wind system and the resultant rainfall, exhibiting great variations in space and time. The monsoons have immense socio-economic implications in India and other parts of South Asia, where great civilisations flourished and vanished in tandem with climate fluctuations. Further, the South Asian monsoons greatly affect the hydrography of the Indian Ocean, as well as terrigenous input from the land to the northern Indian Ocean. Of the two monsoons, the summer (southwest) monsoons are vital to the Indian subcontinent for rainfall and related oceanic processes like upwelling and productivity in the Arabian Sea (Singhvi *et al*., 2007). The role of summer monsoons as a major supplier of energy and water vapour (a major greenhouse gas) in the global climate system has attracted great interest from the scientific community in its efforts to understand and simulate the dynamics and variability of monsoons on different time scales.

Several proxies, such as biological, sedimentological, geochemical, biogeochemical and isotopic parameters have been used extensively in Indian monsoon reconstruction. The accuracy of the climatic reconstructions greatly depends on the quality of the database and a discreet use of proxy indicators. Reconstruction of glacial-interglacial monsoon-controlled precipitation over the Indian

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subcontinent have been attempted using multiple proxy records from land (e.g., Sukumar *et al.*, 1993; Thompson *et al.*, 1997; Enzel *et al.*, 1999; Yadava and Ramesh, 2005) and ocean (e.g., Duplessy, 1982; Sarkar *et al.*, 2000; Thamban *et al.*, 2002; Staubwasser *et al.*, 2003; Gupta *et al.*, 2003, 2005). For several decades, micropalaeontologists have used faunal and pollen records of sediments from the northern Indian Ocean to infer past variations in biological productivity as well as monsoon-related sea surface temperature and salinity changes (e.g., Duplessy, 1982; Naidu and Malmgren, 1995; Gupta *et al.*, 2003). Independently, chemical and isotopic proxy studies have been used to differentiate and quantify the same parameters (Sirocko *et al.*, 1993, 2000; Cayre and Bard, 1999; Schulte *et al.*, 1999; Sarkar *et al.*, 2000; Kudrass *et al.*, 2001; Lückge *et al.*, 2001; Thamban *et al.*, 2001; Suthhof *et al.*, 2001; Staubwasser *et al.*, 2003). The various complicating factors involved in the application of these proxies mean that the proxies need not necessarily all provide synchronous results.

The early Holocene embodies the northern Hemisphere "climatic optimum", when the incoming solar radiation increased substantially and the glacial boundary conditions were at a minimum, leading to diminished land albedo (Prell, 1984). The resultant climate amelioration had a significant effect on the Indian summer monsoon, strengthening the oceanic processes and increasing precipitation on land (Duplessy, 1982; Clemens *et al.*, 1991; Sirocko *et al.*, 1993, 2000; Overpeck *et al.*, 1996; Thamban *et al.*, 2002). Summer monsoon records from the NW Arabian Sea (Oman margin) revealed that summer monsoon activity and resultant marine productivity peaked between ~9500 and 5500 calendar years BP (Sirocko *et al.*, 1993; Overpeck *et al.*, 1996). Oceanic records from the Arabian Sea (western Indian Ocean) predominantly provide the summer monsoon variability, whereas records from the Bay of Bengal (eastern Arabian Sea) provide valuable information on the winter monsoon variability. Sedimentary records from the SE Arabian Sea (south Indian margin) indicated that the Holocene humidity maximum occurred during 9000–6500 cal years BP, whereas the palaeoproductivity remained very low, compared to the glacial period (Thamban *et al.*, 2001). Such differential responses within the same basin are an indication of the various complicating factors that could influence the palaeo-monsoon signatures.

Although Holocene climate variability is considered to be much less than that of the last glacial period, recent studies using high-resolution proxy data from the Indian monsoon regime challenge the conventional paradigms and reveal significant, high amplitude, multi-decadal-to-century scale fluctuations (Neff *et al.*, 2001; Doose-Rolinski *et al.*, 2001; Fleitmann *et al.*, 2003; Gupta *et al.*, 2003, 2005; Staubwasser *et al.*, 2003; Hong *et al.*, 2003; Wang *et al.*, 2005). Recent studies also connect the abrupt fluctuations in the Asian summer monsoon with the North Atlantic climate (Gupta *et al.*, 2003, 2005; Wang *et al.*, 2005), which may be linked to abrupt reorganisations of the thermohaline circulation, leading to a redistribution of energy, changing the temperature and moisture gradient over the southern subtropical Indian Ocean (Hong *et al.*, 2003). Studies have also revealed the intricate relationship between the monsoons and the flourishing and collapse of great civilisations in India (e.g., Enzel *et al.*, 1999; Pandey *et al.*, 2003; Staubwasser *et al.*, 2003; Gupta *et al.*, 2006).

Several mechanisms may act on the monsoons on various time scales. Most of the observed natural variations during the late Quaternary, were ascribed to the orbital and solar variations. However, a growing body of data from the tropical monsoon regime supports a persistent solar influence on the monsoon oscillations, at least during the Holocene (Neff *et al.*, 2001; Agnihotri *et al.*, 2002; Fleitmann *et al.*, 2003; Gupta *et al.*, 2003, 2005; Staubwasser *et al.*, 2003; Tiwari *et al.*, 2005). Recently a 11,000 yr reconstruction of sunspots using tree ring $\Delta^{14}C$ data revealed exceptional changes in sunspot activity within the Holocene (Solanki *et al.*, 2004). Since sun is the principal source of energy, changes in solar energy output can bring about major changes in the climate systems (Kodera, 2004; Mayewski *et al.*, 2004; Hameed and Lee, 2005). Nevertheless, a mechanism by which small (~0.1%) changes in solar energy output during the solar cycle influencing the climate has recently been a topic of intense debate.

We discuss here a well-resolved Holocene sedimentary proxy record from the eastern Arabian Sea in conjunction with a suite of published, well-dated, sedimentary records from the Arabian Sea basin. The main objective of this study is to understand the timing of short-term variations in the Holocene summer monsoon precipitation/marine productivity as well as to synthesise a basin-wide scheme of monsoon events and the possible forcing mechanisms.

## 2. Regional Settings, Oceanography and Geology

Monsoons are the seasonally reversing winds which bring rain to the Indian subcontinent and cause upwelling along the continental margins. This seasonal reversal of the wind direction between summer and winter drives the summer (southwest) and winter (northeast) monsoons in the Indian Ocean and precipitation over south Asia. In summer, differential heating of the continental and oceanic regions leads to low atmospheric pressure above the Asian Plateau and high atmospheric pressure over the relatively cool southern Indian Ocean, resulting in a strong, low-level jet stream (Findlater Jet). Much of the intensity of this jet derives from the direct heating of the troposphere above Asia and through latent heat collected over southern subtropical ocean, which is transported across the equator and released by precipitation over South Asia (Clemens *et al.*, 1991). The winter monsoon is characterised by low seasonal insolation over Asia and relatively high albedo due to the seasonal snow cover. These boundary conditions produce a high pressure cell in the low-level atmosphere over South Asia which results in a northeasterly wind flow over the Arabian Sea, which is weak and carries little moisture.

The surface circulation in the Arabian Sea is also modulated by the seasonal variation of the monsoon wind system. The seasonal reversals of the surface wind field over the tropical Indian Ocean are far more dramatic than in other regions at low latitudes, and these reversals have a profound impact on the seasonal variation of the surface current system (Clemens *et al.*, 1991). During the summer monsoon (June–September), the low level southeasterly trade winds of the Southern Hemisphere extend across the equator to become southerly or southwesterly in the Northern Hemisphere. The frictional stresses of these in turn drive the Somali current, the westward flowing South Equatorial Current, and the eastward flowing southwest Monsoon Current (Wyrtki, 1971). Oceanic circulation during the winter monsoon season is relatively weak and is characterised by the North Equatorial Current, an eastward flowing Equatorial Counter Current, and a moderately developed anticyclonic gyre.

During the summer monsoon, the Findlater Jet induces strong upwelling along the western Arabian Sea margin (off the Oman coast). Although low to moderate upwelling also occurs along the south Indian margin during the summer monsoon, the dynamics in this case are entirely different (Shetye *et al.*, 1990; McCreary *et al.*, 1993). The strong, regularly alternating monsoon winds drive all processes of production in the Arabian Sea and the resultant biological productivity shows strong seasonal variations in relation to the seasonal monsoon cycles. The high rate of input of organic matter and its subsequent oxidation below the thermocline is associated with a very high oxygen demand at intermediate depths. The resulting oxygen deficiency is fostered by the sluggish intermediate water circulation, leading to a pronounced Oxygen Minimum Zone (OMZ) between 150 to 1500 m water depth in the Arabian Sea (Wyrtki, 1971).

Geologically, the Deccan Trap basalts constitute the characteristic rocks exposed to the north of Goa. Precambrian gneisses, schists and charnockites are the predominant rocks in the region south of Goa. Summer monsoons account for most of the very high average annual rainfall recorded in the Indian peninsula (>3000 mm), whereas winter monsoons are insignificant as far as rainfall is concerned. South of 20°N, the Western Ghats mountain range with elevations up to ~1000 m, plays a major role in controlling the rainfall intensity over the west coast of India. Numerous rivers originate from and drain through the steep slopes of this mountain range and discharge ~100 km$^3$ water annually into the eastern Arabian Sea (Rao, 1979). The terrigenous sediments of the central and southwestern continental margin of India consist predominantly of river-borne clays and the aeolian fraction is negligible (Rao and Rao, 1995).

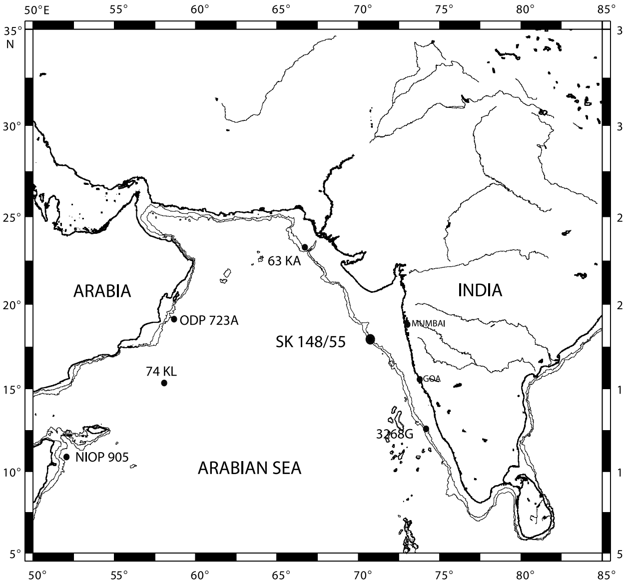

Fig. 1. Map showing the location of core SK 148/55 site and locations of other cores used in the present study.

## 3. Materials and Methods

Gravity core SK 148/55 (length - 6.13 m; location - 17°45′ N, 70°52′ E) was collected during the 148th expedition of the *ORV Sagar Kanya* from 500 m water depth within the core of the Oxygen Minimum Zone (OMZ) along the Western continental margin of India (Fig. 1). The organic-rich sedimentary sequences had a strong hydrogen sulphide odour as well as light, distinct to indistinct dark and light laminations up to 550 cm depth. The lithology changes drastically below this depth. The Sr-Nd isotope and clay mineral study of this core reveals a weathered volcanic source, similar to that of the hinterland Deccan Trap rocks (Kessarkar *et al.*, 2003).

Chronological control was obtained by AMS $^{14}$C dates at representative intervals on hand-picked, ultrasonically cleaned, monospecific foraminifera *Globigerinoides ruber* (white) at the Leibniz Laboratory of the University of Kiel, Germany (Table 1). This robust chronological control provided a continuous Holocene succession up to 550 cm, followed by a hiatus in sedimentation between the Holocene and the Last Glacial

Table 1. Conventional AMS $^{14}$C ages on hand-picked *G. ruber* species from SK 148/55, together with the calibrated calendar ages*.

| Lab. code No. | Depth (cm) | Conventional $^{14}$C age (Year B.P.) | Calibration intervals (Year B.P.) | Calibrated age (Year B.P.) |
|---|---|---|---|---|
| KIA15946 | 4–6 | 865 ± 30 BP | 286–413 | 350 |
| KIA15947 | 92–94 | 2440 ± 30 BP | 1809–1968 | 1890 |
| KIA15948 | 190–192 | 4420 ± 40 BP | 4253–4441 | 4350 |
| KIA15949 | 302–304 | 6995 ± 45 BP | 7283–7415 | 7350 |
| KIA15950 | 392–394 | 8250 ± 50 BP | 8435–8632 | 8530 |
| KIA15951 | 482–486 | 8810 ± 50 BP | 9231–9421 | 9330 |
| KIA15952 | 528–532 | 8970 ± 60 BP | 9389–9542 | 9470 |

*AMS $^{14}$C measurements were carried out at the Leibniz Laboratory, University of Kiel, Germany. Calibration to calendar ages were done following Stuiver and Reimer (1993) using the latest marine calibration data (marine04 database; Hughen *et al.*, 2004), with a reservoir correction of 541 ± 587 years (Southon *et al.*, 2002).

Maximum (LGM), which is also evidenced from the dramatic variations in lithology and other proxy records. In the present study we consider only the upper 550 cm of the sediment core, representing the nearly complete Holocene succession, having seven AMS $^{14}$C dating points (Table 1; Fig. 2). An age model was then obtained by applying a reservoir age correction of 541 ± 58 ($\Delta$R 165 ± 57) years to the $^{14}$C dates, based on the available $^{14}$C measurements on bivalves collected from a very nearby location (Southon *et al.*, 2002). Although Staubwasser *et al.* (2002) reported changing reservoir ages during the Holocene in a core off Pakistan, this may not be significant our study region since the core site does not experience any significant monsoon-related upwelling. The conventional AMS $^{14}$C dates were calibrated into calendar ages using the well-known CALIB program (CALIB rev5.0.2) using the latest database (Stuiver and Reimer, 1993; Revision 5.0) and linearly interpolated to provide a continuous age scale. The chronology thus obtained revealed that the sediment accumulation rate was extremely high (up to 1.83 mm/year) during the early Holocene and moderate (up to 0.40 mm/year) during the middle-to-late Holocene period. Such high sedimentation rates enable us to interpret the short-term (centennial) events within the Holocene.

The magnetic susceptibility ($\kappa$) measurements were carried out at every 2 cm interval (total 276 samples) using a Magnetic Susceptibility meter and a Dual Frequency Sensor (Bartington MS2). Organic carbon and nitrogen measurements were carried out at 6 cm intervals using a CNS Elemental Analyser (Carlo Erba NCS 2000).

Major and minor elemental chemistry was carried out at every 10 cm interval after open acid digestion of the sediment samples in a clean environment. Ultra-pure (18.7 MΩ) water freshly obtained from a Millipore™ (Milli-Q Element) system was used for all purposes. Complete digestion of the samples was ensured by repeated digestion. The samples were first treated with ultrapure $HClO_4$ (5 ml), HCl (2.5 ml), $HNO_3$ (2.5 ml) and HF (5 ml) and kept overnight on a hotplate at 100°C. On the morning of the following day, the temperature was raised to 140°C and maintained for 2 hours. After cooling, the samples were treated with HCl (1.5 ml), $HNO_3$ (1.5 ml) and HF (3 ml). The samples were then kept overnight at 140°C. On the morning of the third day, the temperature was raised 170°C and held there until the samples had completely dried (~1 hour). Thereafter the samples were

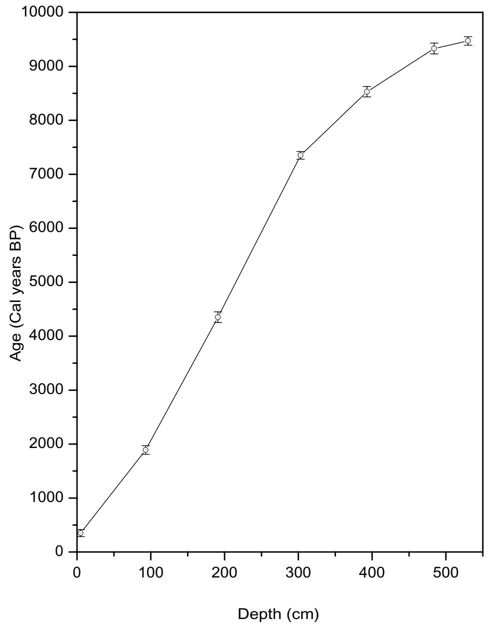

Fig. 2. Age-depth model of SK 148/55 with error (1$\sigma$) in age estimation.

cooled to room temperature and treated with HCl (1.5 ml), $HNO_3$ (1.5 ml) and HF (3 ml) and heated at 170°C to dryness (~6–8 hours). The samples were again allowed to cool to the room temperature and thereafter 3 ml of $HNO_3$ was added to the digested samples, which were warmed at 80°C for 15 minutes to bring all material into solution. The digested samples were transferred to very clean (acid and Milli-Q cleaned), pre-weighed 100 ml PP bottles. The Teflon beakers were washed several times with Milli-Q water to ensure complete transfer of samples. Geochemical measurements were carried out using an ICP-AES system (Seiko SPS 7800). Accuracy of the measurements was ensured by runs of blanks and several repeated measurements of the international standards prepared by the Geological Survey of Japan (JA2, JB2, JG1A, JR1), digested along with the sediment samples. The relative standard deviation estimates based on repeated analysis of standards for all elements discussed here are better than ±10%.

In addition to the terrigenous proxy analysis of core SK 148/55, we have also complied a synthesis of the Holocene data available from other sediment cores from the Arabian Sea basin. Such an exercise helps us to understand the timing of major abrupt monsoon events during the Holocene as well as providing a basin-wide palaeomonsoon sequence. Although several sedimentary records are available for the Holocene Indian monsoons, only those records which are regionally representative, with high sampling resolution (~200 years) and reliable chronological control based on AMS $^{14}C$ dating are used for this synthesis. It should be noted that all ages described here are calibrated into calendar years after applying regional/local reservoir age corrections.

## 4. Results and Discussion

Based on the Sr-Nd isotope study on the clay fraction of the samples of core SK 148/55, it is evident that the fluvial-derived volcanic material weathered from the hinterland Deccan Traps constitutes the main source of terrigenous sediments (Kessarkar *et al.*, 2003). However, the sediment sequences are dominated by biogenic carbonates (foraminifera and coccolithophores) throughout (>70%), compared to lithogenic input. This high carbonate flux to the core site may thus act as a major diluent of the magnetic minerals. In order to ditermine whether the magnetic susceptibility records are a reliable proxy for terrigenous supply or whether it is dominated by the dilution effects of biogenic carbonate flux, we plotted the calcium carbonate content together with other known terrigenous records (Fig. 3). The carbonate data reveal no significant relation to the magnetic susceptibility and other elemental proxy records. Thus the magnetic susceptibility data of core SK 148/55 are independent of the carbonate dilution effects. To further substantiate this, we have recalculated all the elemental data (Fe, Ti and Al) on a carbonate-free basis (element% cfb = [element%/lithogenic%]*100). The records thus obtained are independent of carbonate dilution and their close relation with the magnetic susceptibility data confirms that all these records are indeed reliable proxies for precipitation changes in the study region.

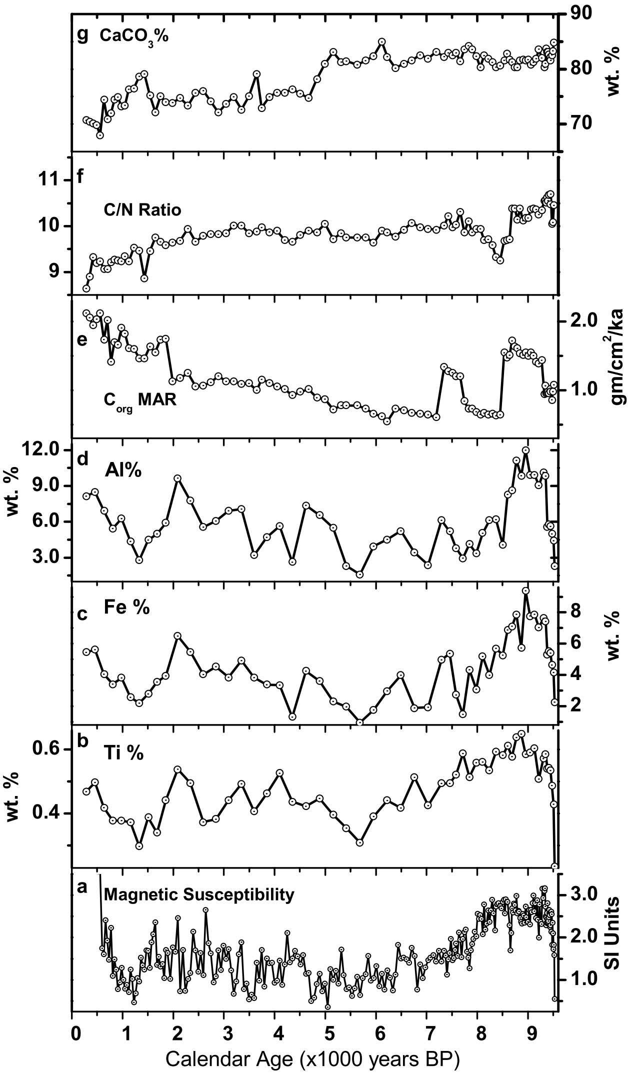

Fig. 3. Terrigenous proxy records of core SK 148/55. a) Magnetic susceptibility; b) Ti %; c) Fe %; d) Al %; e) accumulation rate of organic carbon fraction; f) C/N ratio; g) $CaCO_3$ %.

The high-resolution time series of magnetic susceptibility data provides a sampling resolution of ~10 years during the early Holocene and ~50 years during the middle and late Holocene period. The magnetic susceptibility values varied subtly, yet significantly, between 0.35 and 3.56 with relatively higher values obtained during the early and late Holocene (Fig. 3a). Elemental proxies like Fe, Ti and Al (all reported on a carbonate-free basis) also exhibited similar variations throughout, strongly supporting a common origin of the signals as well as the reliability of the magnetic susceptibility records. The titanium (Ti) concentration varied between 0.24 and 3.16%, whereas that of iron (Fe) varied between 0.95 and 9.38% (Figs. 3b and c). The aluminium (Al) concentration varied between 1.60 and 12.0%, with similar trends to that of Fe (Fig. 3d). All records revealed similar patterns with greatly increased concentrations during the early Holocene and subsequent large oscillations towards the end of the period. The estimated mass accumulation rates (MAR) of lithogenic fraction (non-carbonate fraction, to be precise) varied between 5 and 30 g/cm$^2$/ka (figure not shown) and that of organic carbon ($C_{org}$) between 0.54 and 2.12 g/cm$^2$/ka (Fig. 3e).

### 4.1 *Timing and implications of the Holocene monsoon oscillations*

The terrigenous records of core SK 148/55 reveal that the most impressive, well-resolved environmental variations are evidenced during the early Holocene, associated with abrupt, short-term oscillations in the terrigenous signals. The monsoon reached its peak about 9500 and 8000 years BP, as supported by various terrestrial proxies like magnetic susceptibility and element concentrations (Fig. 3). This is coeval with the maxima in Indus discharge as well as the establishment of thermocline anoxia in the Arabian Sea (Staubwasser *et al.*, 2002). Another prominent event is again observed starting at 9100 years BP, wherein, within a span of few decades, the Fe concentration increased significantly, suggesting a significant increase in precipitation-derived terrigenous supply to the core site. The present study thus precisely brackets the early Holocene Indian monsoon intensification as occurring in two abrupt steps at 9400 and 9100 years BP, with the main event between 9100 and 8500 years BP, thus refining earlier interpretations (Sirocko *et al.*, 1993; Overpeck *et al.*, 1996; Prins and Postma, 2000). Such an abrupt, multi-decadal event was also inferred in the monsoon-induced upwelling in the NW Arabian Sea with an abrupt change in G. bulloides percentage at ~9000 years BP (Gupta *et al.*, 2003). The C/N ratios of organic matter varied between 8.6 and 10.7, with relatively higher values (10.4–10.7) during the early Holocene (Fig. 3f). These values suggest that organic matter is predominantly marine (C/N 7–9), whereas some mixing of nitrogen-poor terrestrial organic matter (C/N > 15) seems to have occurred during the early Holocene due to the enhanced lithogenic input.

Complementary to the earlier findings, we note that unlike the intensification, the end of the early Holocene precipitation event occurred in a less dramatic manner starting at 8500 years BP (Fig. 3). This event is synchronous with the first aridification stage of the Sahara (Jung *et al.*, 2004). A sudden decrease in Indus discharge at 8400 years BP in the NE Arabian Sea has also been suggested to indicate the cessation of the early Holocene summer monsoon event (Staubwasser *et al.*, 2002). It is evident that abrupt changes in summer monsoons were common within the broad early Holocene precipitation maxima, as supported by the high-resolution data from speleothem records of northern Oman as well as the Oman margin sediments (Neff *et al.*, 2001; Gupta *et al.*, 2003). Our studies also reveal a significant weakening of the Indian monsoon starting at ~7000 years BP, which is synchronous with the starvation of the Indus/Makran Fan system (Prins and Postma, 2000). A combination of archaeological and other land records in the Indian subcontinent also supports a substantial weakening of the summer monsoon around 7000 years BP (Gupta *et al.*, 2006).

One of the most significant weak monsoon periods is recorded in our studies between 6000 and 5500 years BP. This event is well preserved in the records of all terrigenous proxies like Fe, Al and Ti (Fig. 3). Such an event is also well demonstrated in the planktonic foraminiferal oxygen isotope records of sediment cores from the southwest coast of India, which have been interpreted as a substantial decrease in precipitation related to Indian summer monsoon (Sarkar *et al.*, 2000; Thamban *et al.*, 2001). A substantial decrease in summer monsoon precipitation during 5600 years BP was also recorded as a reduction of kaolinite/chlorite ratio (Thamban *et al.*, 2002). Reduced precipitation around 5500 years BP is also recorded in the Dongge Cave stalagmite of Southern China, which is one of the most well-resolved terrestrial monsoon records currently available (Wang *et al.*, 2005). The above period also matches the decreased biological productivity in the Oman margin (Gupta *et al.*, 2005). Another weak summer monsoon event is observed in the terrigenous proxy record around 3500 years BP. Records of Sarkar *et al.* (2000) also suggests such a change in Indian summer monsoon precipitation. Although this period also falls within the broad period of diminished Indus freshwater input between 4500 to 3000 years BP, there seems to be some increase in rainfall around 3500 years BP, which may be attributed to winter/spring rainfall (Staubwasser *et al.*, 2003).

The late Holocene indicates a rapid decrease in terrigenous supply at 1300 years BP (Fig. 3). A severe weakening of the summer monsoon activity around 1500 years BP is evident in the Arabian Sea upwelling (Gupta *et al.*, 2003) as well as historical records from India (Pandey *et al.*, 2003). A persistent increase in terrigenous supply is evident after this interval until ~500 years BP, which may coincide with the Medieval Warm Period (MWP ~800–1200 year AD) as recorded in several North-

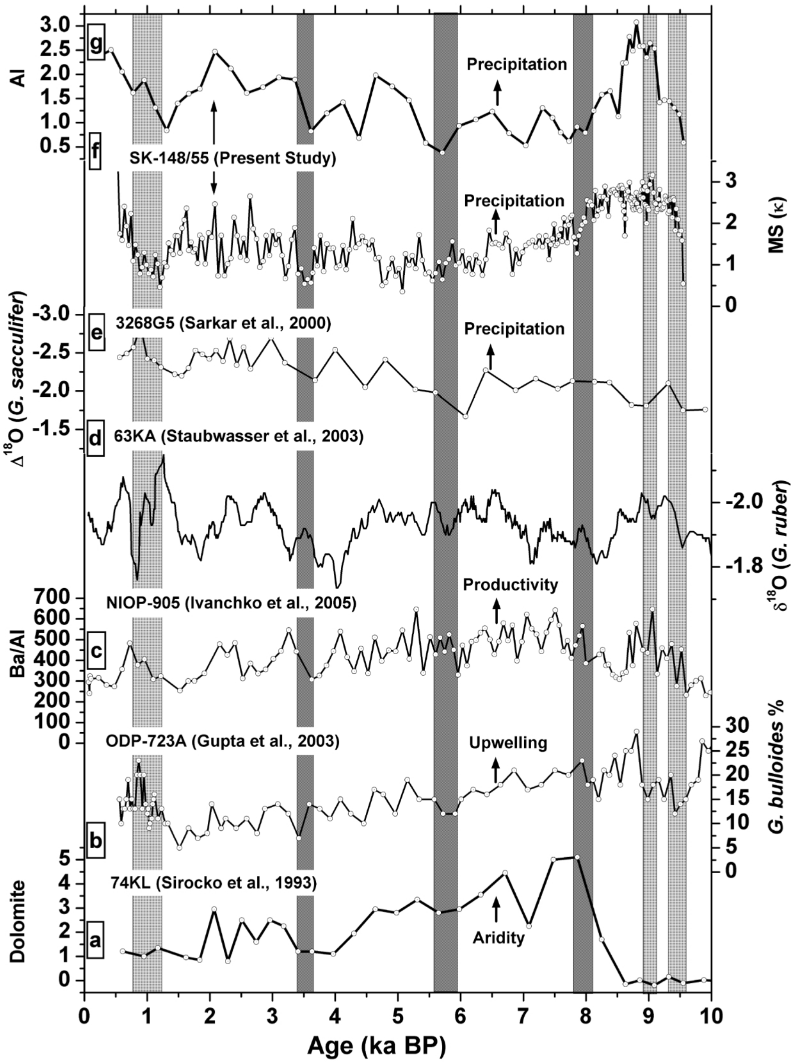

Fig. 4. Synthesis of Holocene variations in the summer monsoon as recorded in the Arabian Sea. a) Aridity records off Arabian margin (Sirocko *et al.*, 1993); b) Monsoon wind-induced upwelling record off Oman margin (Gupta *et al.*, 2003); c) Biological productivity records off Somali margin (Ivanochko *et al.*, 2005); d) Precipitation records off Indus river mouth (Staubwasser *et al.*, 2003); e) E-P records off Southwest Indian margin (Sarkar *et al.*, 2000); f) and g) Precipitation records of the present study. For core locations, see Fig. 1. All ages are in calendar years before present after reservoir correction, calibrated using recent database (see text).

ern Hemisphere records within the chronological uncertainties.

### *4.2 Regional synthesis of Holocene monsoon events*

In order to identify the regionally relevant and consistent events related to the Indian summer monsoon, we have correlated our records with the available Holocene data from the Arabian Sea (Fig. 4). Although large quantities of published records are available for this part of the world ocean, we have considered only selected, high-resolution, high-quality (AMS $^{14}$C-dated, corrected and calibrated) records that are regionally representative. The literature database considered for the present synthesis study includes: Sirocko *et al.* (1993), Sarkar *et al.* (2000), Staubwasser *et al.* (2003), Gupta *et al.* (2003, 2005), and Ivanochko *et al.* (2005). Some of the records represent monsoon-induced precipitation/aridity changes, whereas a few of the others represent either the oceanic productivity or upwelling records (Fig. 4). Records off the Indus River mouth are unique in that the $\delta^{18}$O changes at this site mainly represent the mixture of spring rainfall and melt water input from Himalayan glaciers (Staubwasser *et al.*, 2003). It is therefore obvious that these records will be different from all other monsoon

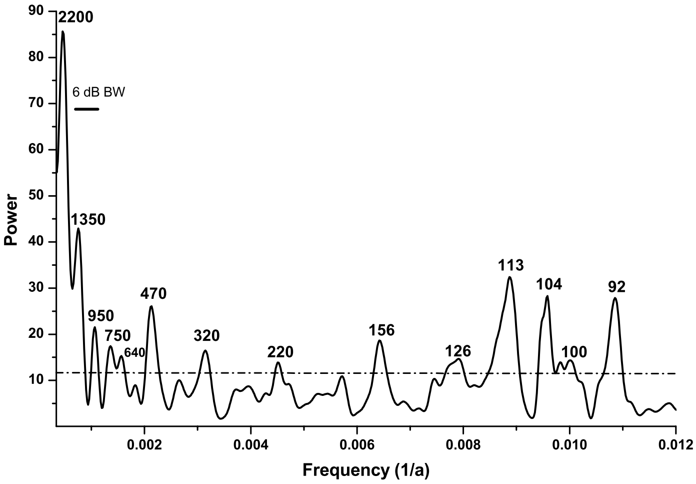

Fig. 5. Frequency analysis of magnetic susceptibility data of core SK 148/55. The dotted line corresponds to the 95% significance level and the horizontal short bar denotes the 6 dB bandwidth.

records described here, which are mainly representative of summer monsoon rainfall and resultant ocean processes.

A summary of the major, regionally consistent, rapid climate events thus identified in this study as well as in comparison with other records from Arabian Sea is as follows:

1. The early Holocene intensification of summer monsoons occurred in two steps at 9500 and 9100 ka BP. This is also clearly evident in the records of Gupta *et al.* (2003) and Ivanochko *et al.* (2005).

2. A significant decrease in monsoon intensity at 8500–8000 years BP. Strongly manifested in the dolomite (aridity proxy) record of Sirocko *et al.* (1993) as well as upwelling record of Gupta *et al.* (2003, 2005).

3. A mid-Holocene arid event around 6000–5500 years BP, wherein both precipitation and oceanic productivity remained low. This is well demonstrated in the record of Sarkar *et al.* (2000), Thamban *et al.* (2001, 2002) and Gupta *et al.* (2003, 2005).

4. During the late Holocene, monsoon conditions again deteriorated around 3500 years BP. This is evident in the present study as well as that of Sarkar *et al.* (2000) and Ivanochko *et al.* (2005).

5. Around 1600 years BP, a deterioration of the summer monsoon intensity is recorded, followed by a substantial enhancement around 1000 years BP. These events are also evident in the records of Sarkar *et al.* (2000), Gupta *et al.* (2003) and Ivanochko *et al.* (2005). However, there is a conspicuous mismatch in the records of freshwater input by the Indus River during the same period, possibly due to the fact that these records represent the winter/spring rainfall (Staubwasser *et al.*, 2003).

The major monsoon events described by the present synthesis of marine records from the Arabian Sea basin appears to be synchronous with the Holocene "Rapid Climate Change" (RCC) events extracted from several globally distributed, multi-archive, multi-proxy records (Mayewski *et al.*, 2004). Assuming that the dating uncertainties are not very significant, it is suggested that the differences in proxy responses could be an artefact of the different response time of proxies to the same forcing mechanism.

### 4.3 *Role of solar variability on Holocene monsoon oscillations*

On a millennial scale, the mechanism for switches in monsoon state is directly related to the relative heating of the Tibetan plateau and mid-latitude atmospheric moisture conditions (Higginson *et al.*, 2004). The persistent oscillations observed within the various proxy records throughout the Holocene suggest that cyclicity is inherent to the low latitude climate systems. In order to examine this as well as to understand the role of various monsoon forcing mechanisms, we carried out power spectrum analysis of the time series records of terrigenous proxies using the SPECTRUM program, which uses a Lomb-Scargle periodogram for the unevenly spaced data (Schulz and Stattegger, 1997). Since the terrigenous elemental data closely correlate with the magnetic susceptibility records and since they give the highest temporal resolution (decadal to multi-decadal), we used the time series of magnetic susceptibility data for the spectral analysis. The power spectrum reveals a hierarchy of statistically significant (95% significance level) periodicities centred at 2200, 1350, 950, 750, 470, 320, 220, 156, 126, 113, 104 and 92 years (Fig. 5). Many of these cycles have also been confirmed using the Multitaper Method (MTM) and seems to be consistent in nature.

The 2200 year periodicity in monsoons was initially noticed in the sediment records off Oman and was ascribed to the interactions between the oceanic circulation and atmospheric $^{14}C$ variations (Naidu and Malmgren, 1995). Since an increase in $^{14}C$ production rates is attributed to the lower solar activity and a reduced shielding of earth from cosmic particles by the solar magnetic field, the atmospheric $^{14}C$ variations as estimated from tree ring records are considered to be a direct proxy for solar activity (Stuiver and Braziunas, 1993). The tree ring $^{14}C$ records indeed reveal a 2200 year periodicity (Stuiver and Braziunas, 1993; Lean, 2002), suggesting a solar origin for this cycle. However, oceanic circulation may play a significant role in transferring and modulating these signals. The 1350 year cyclicity is similar to the enigmatic "1500 years" periodicity first observed in the North Atlantic ice rafted debris (IRD) records, which reveal a cycle of 1340 ± 500 years, believed to be influenced by variations in the solar energy output (Bond *et al.*, 2001). Although the existence of such cycles in the North Atlantic climatic regime has been disputed, similar cyclicity has been reported not only in the high latitudes, but also in low latitude monsoon domains (Mayewski *et al.*, 1997; Gupta *et al.*, 2005). The periodicity of 950 years is widely reported in stalagmites from Oman (Neff *et al.*, 2001), lake sediments from Alaska (Hu *et al.*, 2003), and the Northern Hemisphere tree ring $\Delta^{14}C$ data (Lean, 2002). The hemisphere-wide presence of this periodicity confirms its global nature and its presence in $\Delta^{14}C$ data support its origin, which is related to variations in the solar activity.

Among the series of cycles observed, the most important periodicity commonly attributed exclusively to the South Asian monsoon regime is the ~750 year cycle, reported from the varve sediments off Pakistan (von Rad *et al.*, 1999; Staubwasser *et al.*, 2003), western Indian margin sediments (Sarkar *et al.*, 2000), and the stalagmites from Oman (Neff *et al.*, 2001), as well as the South China Sea sediments (Wang *et al.*, 1999). Although this periodicity is widespread within the low latitude monsoon systems, it has been suggested that it is related to the global oceanic thermohaline circulation by controlling the incorporation of the $^{14}C$ into the ocean (Neff *et al.*, 2001). A significant coherence was obtained between the global $^{14}C$ production rate and the monsoon precipitation record (deduced from planktonic foraminiferal $\delta^{18}O$ data) within the 630–780 year band throughout the Holocene (Staubwasser *et al.*, 2003). The presence of this cycle in the tree ring $\Delta^{14}C$ data (Lean, 2002) as well as Asian monsoon records may thus support the extreme sensitivity of low latitude monsoons to subtle variations in solar radiation levels.

The prominent 470 year cyclicity observed in our magnetic susceptibility data is similar to the 490 year cycle found in the varve thickness (proxy for precipitation changes) off Pakistan, which was supposed to be of possible tidal origin (Berger and von Rad, 2002). However, we find that a similar (~500 year) cyclicity is obtained within the tree ring $\Delta^{14}C$ time series spectrum (Lean, 2002), suggesting a possible solar influence. The cycles observed in our data at 320, 220, 156, 126 and 113 years have been reported from the Indian monsoon domain based on a variety of climate proxies (Neff *et al.*, 2001; Agnihotri *et al.*, 2002; Berger and von Rad, 2002; Staubwasser *et al.*, 2002; Fleitmann *et al.*, 2003). The frequency analysis of sunspot numbers also reveals the presence of most of these cycles (Gupta *et al.*, 2005). Of these the ~220 year cycle (Suess cycle) is also prominent in Indian monsoon records (Tiwari *et al.*, 2005) and is also present in the $\Delta^{14}C$ data, which is widely ascribed to be of solar origin (Stuiver and Braziunas, 1993). It should also be noted that the strong cyclicity found at 113 years in the data is the same as that obtained by the analysis of the total solar irradiance derived from sunspot activity (Lean *et al.*, 1995; Agnihotri *et al.*, 2002). In the high frequency domain, both the cycles of 104 and 92 years are widely present in the Asian monsoon records and are considered to be of solar origin (Neff *et al.*, 2001; Agnihotri *et al.*, 2002; Fleitmann *et al.*, 2003). However, considering the relatively poor time resolution (~50 years) during the late Holocene, the data quality may not be sufficiently robust to extract periods less than 100 years and they are not discussed in detail here.

Although periodicities by themselves do not necessarily suggest a mechanistic link, they do indicate a possible relation between the monsoon and external forcing factors. The influence of solar activity variations on the Indian monsoon has already been explored based on the presence of some periodicities and coherence at certain bandwidths with respect to the $\Delta^{14}C$ data (Neff *et al.*, 2001; Agnihotri *et al.*, 2002; Staubwasser *et al.*, 2002; Fleitmann *et al.*, 2003). However, the exact mechanisms by which solar variability controls the climate system (especially the low latitude monsoon systems) are only recently being understood (Kodera, 2004; Gupta *et al.*, 2005; Hameed and Lee, 2005; Wang *et al.*, 2005).

Conventional climate modelling output suggests that small variations in solar activity may not lead to significant changes in major forcing factors. However, recent studies report that all these models overlook the various climate amplifiers that are available, especially in the low latitudes (Foukal, 2003). Typically, changes in the total solar irradiance were considered to be responsible for the decadal to centennial climate changes. However, it is extremely difficult to explain the observed regional differences in climate change based on radiative forcing alone. Using modern meteorological datasets and based on available model data, Kodera (2004) suggested that the solar influence on monsoon activity originates from the stratosphere through a modulation of the upwelling in the equatorial troposphere, which produces a north-south seesaw of convective activity in the Indian sector during summer. Increased solar activity would thus increase the convective activity in the equatorial region and would bring higher precipitation over Arabia and India (Kodera, 2004). Such a direct link between solar output and summer monsoon activity was also attributed to the observed close relation between reduced solar input and periods of weakened Indian monsoons during the Holocene (Gupta *et al.*, 2005). Therefore, the direct dynamic response of the troposphere, manifested as a seesaw of convective activity towards an external stimulation of solar activity, seems to be capable of explaining the direct solar modulation of the Holocene monsoon records as well as its regional disparities. It is suggested that throughout the Holocene, externally, small changes in solar activity controlled the Indian monsoon to large extent whereas internally, non-solar causes could have influenced the amplitude of changes.

## 5. Conclusions

The high-resolution terrigenous proxy studies on a laminated sediment core from the Oxygen Minimum Zone of the eastern Arabian Sea margin in conjunction with other available high-resolution sedimentary records provide the temporal sequences of monsoon-controlled precipitation changes during the Holocene. The data suggest that the early Holocene monsoon intensification occurred in two abrupt steps at 9500 and 9100 years BP and weakened gradually thereafter. Broad weakening of monsoons was found at ~8000, 7000, 5500 and 3500 years BP, of which the most significant event was recorded between 6000 and 5500 years BP. Around 1600 years BP, a deterioration of summer monsoon is evident, followed by a major increase in monsoon rainfall 1000 years BP. Most of these events are well represented in several land and marine records from the summer monsoon domains of South Asia, signifying their wide implications. A synthesis of the available marine proxy data from the entire Arabian Sea basin suggests that most of the variations observed in the present study are consistent within the summer monsoon domain, at least during the Holocene. It is suggested that slight differences within the different proxy records could be due to the difference in the response time of the individual proxy to the forcing mechanism. Spectral analysis of the magnetic susceptibility data reveals that significant periodicities do exist at 2200, 1350, 950, 750, 470, 320, 220, 156, 126, 113, 104 and 92 years. Most of these periodicities are very well delineated from the solar proxy records like tree ring $\Delta^{14}C$ data. Throughout the Holocene, persistent changes in the Indian monsoon seem to be stimulated by the sun, suggesting the importance of small changes in solar activity leading to perceptible changes in monsoon conditions.

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## References

Agnihotri, R., K. Dutta, R. Bhushan and B. L. K. Somayajulu (2002): Evidence for solar forcing on the Indian monsoon during the last millennium. *Earth Planet. Sci. Lett.*, **198**, 521–527.

Berger, W. H. and U. von Rad (2002): Decadal to millennial cyclicity in varves and turbidites from the Arabian Sea: hypothesis of tidal origin. *Global Planet. Change*, **34**, 313–325.

Bond, G., W. Showers, M. Cheseby, R. Lotti, P. Almasi, P. deMenocal, P. Priore, H. Cullen, I. Hajdas and G. Bonani (2001): Persistent solar influence on North Atlantic climate during the Holocene. *Science*, **294**, 2130–2136.

Cayre, O. and E. Bard (1999): Planktonic foraminiferal and alkenone records of the last deglaciation from the eastern Arabian Sea. *Quat. Res.*, **52**, 337–342.

Clemens, S., W. L. Prell, D. Murray, G. B. Shimmield and G. Weedon (1991): Forcing mechanisms of the Indian Ocean monsoon. *Nature*, **353**, 720–725.

Doose-Rolinski, H., U. Rogalla, G. Scheeder, A. Lückge and U. von Rad (2001): High-resolution temperature and evaporation changes during the late Holocene in the northeastern Arabian Sea. *Paleoceanography*, **16**(4), 358–367.

Duplessy, J.-C. (1982): Glacial to interglacial contrast in the northern Indian Ocean. *Nature*, **295**, 494–498.

Enzel, Y., L. L. Ely, S. Mishra, R. Ramesh, R. Amit, B. Lazer, S. Rajaguru, V. R. Baker and A. Sandler (1999): High-resolution Holocene environmental changes in the Thar Desert, Northwestern India. *Science*, **284**, 125–128.

Fleitmann, D., S. J. Burns, M. Mudelsee, U. Neff, J. Kramers, A. Mangini and A. Matter (2003): Holocene forcing of the Indian monsoon recorded in a stalagmite from southern

Oman. *Science*, **300**, 1737–1739.

Foukal, P. (2003): Can slow variations in solar luminosity provide the missing link between the Sun and climate? *Eos Trans. AGU*, **84**, 205–208.

Gupta, A. K., D. M. Anderson and J. T. Overpeck (2003): Abrupt changes in Asian southwest monsoon during the Holocene and their links to the North Atlantic Ocean. *Nature*, **421**, 354–356.

Gupta, A. K., M. Das and D. M. Anderson (2005): Solar influence on the Indian summer monsoon during the Holocene. *Geophys. Res. Lett.*, **32**, L17703, doi:10.1029/2005GL022685.

Gupta, A. K., D. M. Anderson, D. N. Pandey and A. K. Singhvi (2006): Adaptation and human migration, and evidence of agriculture coincident with changes in the Indian summer monsoon during the Holocene. *Curr. Sci.*, **90**, 1082–1090.

Hameed, S. and J. N. Lee (2005): A mechanism for sun-climate connection. *Geophys. Res. Lett.*, **32**, L23817, doi:10.1029/2005GL024393.

Higginson, M. J., M. A. Altabet, L. Wincze, T. D. Herbert and D. W. Murray (2004): A solar (irradiance) trigger for millennial-scale abrupt changes in the southwest monsoon? *Paleoceanography*, **19**, PA3015, doi:10.1029/2004PA001031.

Hong, Y. T., B. Hong, Q. H. Lin, Y. X. Zhu, Y. Shibata, M. Hirota, M. Uchida, X. T. Leng, H. B. Jiang, H. Xua, H. Wang and L. Yi (2003): Correlation between Indian Ocean summer monsoon and North Atlantic climate during the Holocene. *Earth Planet. Sci. Lett.*, **211**, 371–380.

Hu, F. S., D. Kaufman, S. Yoneji, D. Nelson, A. Shemesh, Y. Huang, J. Tian, G. Bond, B. Clegg and T. Brown (2003): Cyclic variation and solar forcing of Holocene climate in the Alaskan subarctic. *Science*, **301**, 1890–1893.

Hughen, K. A., M. G. L. Baillie, E. Bard, A. Bayliss, J. W. Beck, C. J. H. Bertrand, P. G. Blackwell, C. E. Buck, G. S. Burr, K. B. Cutler, P. E. Damon, R. L. Edwards, R. G. Fairbanks, M. Friedrich, T. P. Guilderson, B. Kromer, F. G. McCormac, S. W. Manning, C. Bronk Ramsey, P. J. Reimer, R. W. Reimer, S. Remmele, J. R. Southon, M. Stuiver, S. Talamo, F. W. Taylor, J. van der Plicht and C. E. Weyhenmeyer (2004): Marine04 Marine radiocarbon age calibration, 26–0 ka BP. *Radiocarbon*, **46**, 1059–1086.

Ivanochko, T. S., R. S. Ganeshram, G. A. Brummer, G. Ganssen, S. J. A. Jung, S. G. Moreton and D. Kroon (2005): Variations in tropical convection as an amplifier of global climate change at the millennial scale. *Earth Planet. Sci. Lett.*, **235**, 302–314.

Jung, S. J. A., G. R. Davies, G. M. Ganssen and D. Kroon (2004): Stepwise aridification in NE-African deduced from dust borne radiogenic isotope records. *Earth Planet. Sci. Lett.*, **221**, 27–37.

Kessarkar, P. M., V. P. Rao, S. M. Ahmad and G. Anil Babu (2003): Clay minerals and Sr-Nd isotopes of the sediments along the western margin of India and their implication for sediment provenance. *Mar. Geol.*, **202**, 55–69.

Kodera, K. (2004): Solar influence on the Indian Ocean monsoon through dynamical processes. *Geophys. Res. Lett.*, **31**, L24209, doi:10.1029/2004GL020928.

Kudrass, H. R., A. Hofman, H. Doose, K. Emeis and H. Erlenkeuser (2001): Modulation and amplification of climatic changes in the Northern Hemispher by the Indian summer monsoon during the past 80 k.y. *Geology*, **29**, 63–66.

Lean, J. (2002): Solar forcing of climate change in recent millennia. p. 75–88. In *Climate Development and History of the North Atlantic Realm*, ed. by G. Wefer, W. Berger, K.-E. Behre and E. Jansen, Springer-Verlag, Berlin.

Lean, J., J. Beer and R. Bradley (1995): Reconstruction of solar irradiance since 1610: Implications for climate change. *Geophys. Res. Lett.*, **22**, 3195–3198.

Lückge, A., H. Doose-Rolinski, A. A. Khan, H. Schulz and U. von Rad (2001): Monsoonal variability in the northeastern Arabian Sea during the past 5000 years: geochemical evidence from laminated sediments. *Palaeogeogr. Palaeoclimatol. Palaeoecol.*, **167**, 273–286.

Mayewski, P. A., L. D. Meeker, M. S. Twickler, S. Whitlow, Q. Z. Yang, W. B. Lyons and M. Prentice (1997): Major features and forcing of high latitude Northern Hemisphere atmospheric circulation using 110,000-year-long glaciochemical record. *J. Geophys. Res.*, **102**, 26,345–26,366.

Mayewski, P. A., E. E. Rohling, C. J. Stager, W. Karlén, K. A. Maasch, L. D. Meeker, E. A. Meyerson, F. Gasse, S. van Kreveld, K. Holmgren, J. Lee-Thorp, G. Rosqvist, F. Rack, M. Staubwasser, R. R. Schneider and E. J. Steig (2004): Holocence Climate variability. *Quat. Res.*, **62**, 243–255.

McCreary, J. P., P. K. Kundu and R. L. Molinari (1993): A numerical investigation of dynamics, thermodynamics and mixed layer processes in the Indian Ocean. *Prog. Oceanogr.*, **31**, 181–224.

Naidu, P. D. and B. A. Malmgren (1995): A 2200–2400 year periodicity in the Asian monsoon system. *Geophys. Res. Lett.*, **22**, 2361.

Neff, U., S. J. Burns, A. Mangini, M. Mudelsee, D. Fleitmann and A. Matter (2001): Strong coherence between solar variability and the monsoon in Oman between 9 and 6 kyr ago. *Nature*, **411**, 290–293.

Overpeck, J., D. M. Anderson, S. Trumbore and W. Prell (1996): The southwest Indian Monsoon over the last 18,000 years. *Clim. Dyn.*, **12**, 213–225.

Pandey, D. N., A. K. Gupta and D. M. Anderson (2003): Rainwater harvesting as an adaptation to climate change. *Curr. Sci.*, **85**, 46–59.

Prell, W. L. (1984): Variation of monsoonal upwelling: A response to changing solar radiation. p. 48–57. In *Climate Processes and Climate Sensitivity*, ed. by J. E. Hansen and T. Takahashi, Geophysical Monograph Series 29, AGU, Washington, D.C.

Prins, M. A. and G. Postma (2000): Effects of climate, sea level, and tectonics unravelled for last deglaciation turbidite records of the Arabian Sea. *Geology*, **28**, 375–378.

Rao, K. L. (1979): *India's Water Wealth: It's Assessment, Uses and Projections*. 2nd ed., Orient Longman, New Delhi, 267 pp.

Rao, V. P. and B. R. Rao (1995): Provenance and distribution of clay minerals in the sediments of the western continental shelf and slope of India. *Cont. Shelf Res.*, **15**, 1757–1771.

Sarkar, A., R. Ramesh, B. L. K. Somayajulu, R. Agnihotri, A.

J. T. Jull and G. S. Burr (2000): High resolution Holocene monsoon record from the eastern Arabian Sea. *Earth Planet. Sci. Lett.*, **177**, 209–218.

Schulte, S., F. Rostek, E. Bard, J. Rullkotter and O. Marchal (1999): Variations of oxygen minimum and primary productivity recorded in sediments of the Arabian Sea. *Earth Planet. Sci. Lett.*, **173**, 205–221.

Schulz, M. and K. Stattegger (1997): Spectrum: Spectral analysis of unevenly spaced paleoclimatic time series. *Comp. Geosci.*, **23**, 929–945.

Shetye, S. R., A. D. Gouveia, S. S. C. Shenoi, G. S. Michael, D. Sundar, A. M. Almeida and M. Santanam (1990): Hydrography and circulation off the west coast of India during the southwest monsoon. *J. Mar. Res.*, **48**, 359–378.

Singhvi, A. K., K. Rupakumar, M. Thamban, A. K. Gupta, V. S. Kale, R. R. Yadav, A. Bhattacharyya, N. R. Phadtare, P. D. Roy, M. S. Chauhan, O. S. Chauhan, S. Chakravorty, M. Munir Sheikh, N. Manzoor, D. A. Quadir, L. P. Devkota and A. B. Shrestha (2007): Instrumental, terrestrial and marine records of the climate of South Asia during the Holocene: Present status, unresolved problems and societal aspects. In *Monsoon Asia Integrated Regional Studies (MAIRS) SCOPE/START Rapid Assessment Volume* (in press).

Sirocko, F., M. Sarnthein, H. Erlenkeuser, H. Lange, M. Arnold and J.-C. Duplessy (1993): Century scale events in monsoon climate over the past 24,000 years. *Nature*, **364**, 322–324.

Sirocko, F., D. Garbe-Schönberg and C. Devey (2000): Processes controlling trace element geochemistry of Arabian Sea sediments during the last 25,000 years. *Global Planet. Change*, **26**, 217–303.

Solanki, S. K., I. G. Usoskin, B. Kromer, M. Schüssler and J. Beer (2004): Unusual activity of the sun during recent decades compared to the previous 11,000 years. *Nature*, **431**, 1084–1087.

Southon, J., M. Kashgarian, M. Fontugne, B. Metievier and W. W-S. Yim (2002): Marine reservoir corrections for the Indian Ocean and SE Asia. *Radiocarbon*, **44**, 167–180.

Staubwasser, M., F. Sirocko, P. M. Grootes and H. Erlenkeuser (2002): South Asian monsoon climate change and radiocarbon in the Arabian Sea during early and mid Holocene. *Paleoceanography*, **17**, 1063, doi:10.1029/2000PA000608.

Staubwasser, M., F. Sirocko, P. M. Grootes and M. Segl (2003): Climate change at the 4.2 ka BP termination of the Indus valley civilization and Holocene south Asian monsoon variability. *Geophys. Res. Lett.*, **30**, 1425, doi:10.1029/2002GL016822.

Stuiver, M. and T. F. Braziunas (1993): Sun, ocean, climate and atmospheric $^{14}CO_2$: an evaluation of causal and spectral relationships. *Holocene*, **3**, 289–305.

Stuiver, M. and P. J. Reimer (1993): Extended $^{14}C$ data base and revised CALIB 3.0 $^{14}C$ age calibration program. *Radiocarbon*, **35**, 215–230.

Sukumar, R., R. Ramesh, R. K. Pant and G. Rajagopalan (1993): A $\delta^{13}C$ record of late Quaternary climate change from tropical peats in southern India. *Nature*, **364**, 703–706.

Suthhof, A., V. Ittekkot and B. Gaye-Haake (2001): Millennial-scale oscillation of denitrification intensity in the Arabian Sea during the late Quaternary and its potential influence on atmospheric $N_2O$ and global climate. *Global Biogeochem. Cycle*, **15**, 637–649.

Thamban, M., V. P. Rao, R. R. Schneider and P. M. Grootes (2001): Glacial to Holocene fluctuations in hydrography and productivity along the southwestern continental margin of India. *Palaeogeogr. Palaeoclimatol. Palaeoecol.*, **165**, 113–127.

Thamban, M., V. P. Rao and R. R. Schneider (2002): Reconstruction of late Quaternary monsoon oscillations based on clay mineral proxies using sediment cores from the western margin of India. *Mar. Geol.*, **186**, 527–539.

Thompson, L. G., T. Yao, M. E. Davis, K. A. Henderson, E. Mosley-Thompson, P.-N. Lin, J. Beer, H.-A. Synal, J. Cole-Dai and J. F. Bolzan (1997): Tropical climate instability: the last glacial cycle from a Quinghai-Tibetan Ice core. *Science*, **276**, 1821–1825.

Tiwari, M., R. Ramesh, B. L. K. Somayajulu, A. J. T. Jull and G. S. Burr (2005): Solar control of southwest monsoon on centennial timescales. *Curr. Sci.*, **89**, 1583–1589.

von Rad, U., M. Schaaf, K. H. Michels, H. Schulz, W. H. Berger and F. Sirocko (1999): A 5000-yr record of climate change in varved sediments from the Oxygen Minimum Zone off Pakistan, Northeastern Arabian Sea. *Quat. Res.*, **51**, 39–53.

Wang, L., M. Sarnthein, H. Erlenkeuser, P. M. Grootes, J. O. Grimalt, C. Pelejero and G. Linck (1999): Holocene variations in Asian monsoon moisture: a bidecadal sediment record from the South China Sea. *Geophys. Res. Lett.*, **26**, 2889–2892.

Wang, Y., H. Cheng, R. L. Edwards, Y. He, X. Kong, Z. An, J. Wu, M. J. Kelly, C. A. Dykoski and X. Li (2005): The Holocene Asian monsoon: Links to solar changes and North Atlantic climate. *Science*, **308**, 854–857.

Wyrtki, K. (1971): *Oceanographic Atlas of the International Indian Ocean Expedition*. National Science Foundation, Washington, D.C., 531 pp.

Yadava, M. G. and R. Ramesh (2005): Monsoon reconstruction from radiocarbon dated tropical Indian speleothems. *Holocene*, **15**, 48–59.