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The aim of this contribution is to reconstruct sub-orbital changes in the intensity of the Arabian Sea monsoon, a system that dominates climatic change over east Africa, the Arabian Peninsula, Pakistan and western India. This highly populated and culturally dynamic area relies heavily on the precipitation associated with the annual monsoon. Through the determination of the climatic history of this area and by placing evident variations in the tropical monsoon system into a global context, one step is taken towards understanding the mechanisms that propagate rapid climate change. Any anthropogenically-induced climate change can only be determined when the background system is understood.

This study focussed on two sediment cores, one from the Somali margin and one from the Indian margin. These cores span the width of the Arabian Sea and allow two perspectives of the same climate system to be developed. The Somali margin, the genesis of the strong summer monsoon wind jet, is a site of intense summer upwelling and productivity, which results in water column denitrification. The Indian margin receives the torrential seasonal precipitation associated with the rising of the moisture-laden summer monsoon winds. Multi-proxy biogeochemical analysis of the sediments from these two sites has allowed the development of a 90 kyr history of climate change for this area.

In order to fully develop the monsoon reconstruction the following tasks were undertaken:

- The development of a multi-proxy biogeochemical history of environmental change in the western Arabian Sea using the sediments of core 905 from the Somali margin.
- The sampling of core MD76-131 from the Indian margin and development of a multi-proxy biogeochemical history of environmental change in the eastern Arabian Sea
- The construction of chronologies for core 905 and for core 131 in order to meaningfully compare these two sites.
- The comparison of the Arabian Sea monsoon variability with global records of environmental change.
This work has contributed a high resolution 90 kyr history of climate change in a region capable of impacting global climate. In this final chapter I will briefly summarise this contribution.

**Figure 1.** The comparing the Arabian Sea records with Greenland temperatures. **A.** The Indian margin record of denitrification. AMS $^{14}$C dated samples are indicated by blue dots. **B.** The Somali margin record of denitrification. AMS $^{14}$C dated samples are indicated by red dots. **C.** The GISP2 temperature reconstruction. Dansgaard-Oeschger interstadials are numbered 2-20. Heinrich Events (HE 1-6) are highlighted with shaded bands.

The chronologies of cores 905 and 131 are based on radiocarbon dating of samples younger than 35 kyr. The reservoir age corrections and conversion to calendar ages allow these marine cores to then be compared to one another as well as to additional records of climatic change. The AMS $^{14}$C dating determined the ages of the Younger Dryas and Heinrich Events (1-3) “equivalents” in both sediment cores. The close agreement of the timing of these events in the Arabian Sea records with the Greenland ice core GISP2 climatic events, suggests that the monsoon variation nearly synchronous with the Northern Hemisphere temperature variations, commonly
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referred to as Dansgaard Oeschger cycles (Figure 1). The similarity between these three records (supported by $\delta^{18}O$ measurements from sites 131 and 905) allows the assumption of synchronicity (within the error of the dating methods) to be applied and the older sections of both cores 905 and 131 to be tied to the GISP2 $\delta^{18}O$ record where radiocarbon dating is not feasible (see Chapter 3).

![Figure 2. The Arabian Sea summer monsoon reconstruction. A. % Al is a proxy of continental aridity. B. The Fe/Al records indicate increased precipitation over India during periods of enhanced monsoon intensity. C-D Ba/Al and % C$_{org}$ are productivity proxies. E. The denitrification record from the Somali margin. F. Temperature variations over Greenland. Less negative values indicate warmer temperatures.](image)

The core 905 productivity, denitrification and aridity records (see Chapter 4, 6) generate a rounded view of the history of ASSM intensity over the past 90 kyr. Changes in winds strength are deduced using Ba/Al and % C$_{org}$ measurements, which
reflect changes in upwelling-induced productivity and the consequent intermediate water denitrification is determined using the $\delta^{15}$N record. Monsoon related changes in continental moisture are identified by variations in the amount of dust reaching site 905 and the lithogenic records of % Al, % Ti, % Fe and % K (see Chapter 6). It is evident that sub-orbital changes in the strength of the Arabian Sea Monsoon have occurred over the last 90 kyr with increased monsoon intensity, reflected as increased productivity, increased denitrification and decreased continental aridity, coinciding with warm D-O interstadials (Figure 2). The Indian margin record of local precipitation (Fe/Al), which increases when monsoon intensity is strong, is added to the Somali margin records to develop the environmental history of the entire region. (Figure 2) (see Chapter 7).

The seasonality and intensity of the monsoon rainfall over western India has influenced the development of the regional geology. Lateritic deposits that are Fe and Ti-rich but significantly depleted in Si and Ba are common along the west coast of India (Nair et al., 1979; Sahasrabudhe et al., 1979). The deposition of these sediments on the Indian continental slope is evident by the elevated Fe and Ti concentrations and low Si and Ba concentrations in comparison with the average crustal values of these elements (see Chapter 7). The identification of these unique local sediments allows the use of Ba/Al as a productivity proxy in this region despite the low background Ba concentration.

Productivity on the Indian margin also reflects the variability of the summer monsoon, however, elevated $\% \text{C}_{\text{org}}$ and Ba/Al values during glacial periods suggests that the winter monsoon may also have a role to play in this area (see Chapter 9). The cool, dry, winter monsoon wind has its origins in the Himalayas. During the winter months this northeasterly wind induces convective mixing in the northeastern Arabian Sea and a secondary productivity bloom results. During glacial periods, the productivity records of the Indian margin core 131 remain elevated despite a decrease in the summer monsoon intensity, suggesting the winter secondary bloom may be large enough during the glacial periods to impact the sediments of the central Indian margin (Figure 3). The record of denitrification, which also indicates elevated values during glacial periods, supports this conclusion. Heinrich Events, however, appear to be associated with a relative collapse in the summer monsoon system and are correlated with decreased productivity on the Somali margin as well as the Indian
margin (Figure 3). There is no evidence from the central Indian margin sediments indicating that the winter monsoon wind strength increased during Heinrich Events.

Figure 3. Local differences in the Indian margin and Somali margin records. A. The Indian margin record of denitrification. B. The Somali margin record of denitrification. Overall similarities between the two records reflect the dominance of the summer monsoon winds. The increased $\delta^{15}N$ values during the last glacial period (30-15 kyr) reflect local changes, possibly related to the winter monsoon. The dashed lines are to direct the eye and highlight local variability identified as differences between the two records. C. The productivity record from the Indian margin. D. The productivity record from the Somali margin.

When the Arabian Sea monsoon reconstruction is compared to other tropical and low-latitude records of climatic variability, it becomes evident that the entire tropical hydrological cycle is varying on sub-orbital scales, in phase with the northern high latitude temperature shifts. Precipitation records from Socotra Island in the western Arabian Sea (Burns et al., 2003), the Hulu Cave in China (Wang et al., 2001) and the Cariaco Basin off Venzuela (Peterson et al., 2000) all record a northern position of the Intertropical Convergence Zone (ITCZ) during interstadial periods.
when the Arabian Sea summer monsoon intensity is at a maximum (see Chapter 4). A southern ITCZ position is associated with cold stadials and a decrease in the Arabian Sea monsoon intensity. This relationship between the Arabian Sea monsoon and the ITCZ continues throughout the Holocene following the orbital forcing of precession (see Chapter 5). The relationship between the ITCZ and the Arabian Sea summer monsoon suggests that variations in the position, and possibly the concentration, of atmospheric water vapour are a significant component of global climate change.

**Figure 2.** A comparison of tropical climate records and atmospheric greenhouse gas concentrations for the past 90 kyr. Shaded bands indicate the Younger Dryas (YD) and Heinrich Events (H1-6). A. The δ¹⁸O record of Hulu Cave, lighter values indicate
increased summer monsoon rainfall. **B.** Ti measurements from Cariaco Basin. Increased concentrations indicate local precipitation increases which results in more terrestrial runoff (Petersen et al., 2000) **C.** The atmospheric methane record measured from the Byrd ice core, Antarctica (Blunier et al., 1998). **D.** The atmospheric methane record measured from the GISP2 ice core (Brook et al., 1996). **E.** Atmospheric N$_2$O concentrations measured from the GISP2 ice core (grey) (Flückiger et al., 2004; Flückiger et al., 1999). GRIP and NGRIP high-resolution N$_2$O data for D-O event 8-12, 19-20 and the Bølling-Ållerød (32, 33), presented on the GISP2 timescale (black). **F.** The core 905 nitrogen isotope record. Values heavier than 5 ‰, the mean ocean value, indicate denitrification. **G.** The % Al concentrations from core 905 indicates changes in amount of lithogenic material reaching site 905. **H.** Atmospheric dust reconstructions from Greenland and Antarctica. The GISP2 (black) record is laser light scattering data (Ram et al., 1997). The Vostok (grey) record is dust volume concentration in $10^{-9}$ cm$^3$ / g of ice (Petit et al., 1990). The Vostok record is on the Blunier time scale for GISP2 (Blunier et al., 1998).

Changes in the tropical hydrological cycle produce significant feedbacks that have global climate repercussions (see Chapter 4). The tropics are a major source of greenhouse gases and atmospheric aerosols, both of which are mediated by the moisture content of the tropical and sub-tropical soils. Tropical wetland areas emit both methane (CH$_4$) and nitrous oxide (N$_2$O) and the atmospheric concentrations of these gases have been reconstructed from air bubbles trapped in polar ice (Blunier et al., 2001; Blunier et al., 1998; Brook et al., 1999; Flückiger et al., 2004; Flückiger et al., 1999; Flückiger et al., 2002; Sowers et al., 2003). The deflation of dust increases when soil moisture decreases and sub-tropical semi-arid regions are the largest producers of atmospheric dust (Pye, 1989), the history of which is also recorded in polar ice (Petit et al., 1990; Ram et al., 1997). A comparison of the Arabian Sea monsoon reconstruction with ice core CH$_4$, N$_2$O and dust records identifies a convincing relationship between increased monsoon intensity and increased atmospheric concentrations of greenhouse gases, as well as between decreased monsoon intensity and increased atmospheric dust (Figure 4).

The 90 kyr reconstruction of the Arabian Sea summer monsoon identifies a coherent mechanism linking variations in tropical aridity with the marine and terrestrial greenhouse gas emissions of water vapour, CH$_4$, and N$_2$O on sub-orbital time-scales. Through greenhouse gas feedbacks, rearrangement of low-latitude convection patterns could amplify and perpetuate millennial-scale climate changes. This contribution determines that transitions in the integrated tropical hydrological cycle are a critical component of the persistent rapid climate changes that are evident in paleoclimate records.
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