CHAPTER 3

Variations in Tropical Convection as an Amplifier of Global Climate Change at the Millennial Scale

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Abstract

The global expression of millennial-scale climatic change and the persistence of this signal in Holocene records point to atmospheric teleconnections as the mechanism propagating rapid climate variations. We suggest rearrangements in the tropical convection system globally affected the concentration and location of atmospheric water vapour and modulated terrestrial and marine emissions of \text{CH}_4 and \text{N}_2\text{O}, providing a tropical mechanism of amplifying and perpetuating millennial-scale climatic changes. A multi-proxy reconstruction of the intensity of the Arabian Sea Summer Monsoon shows strong millennial-scale variability over the past 90 kyr in which low intensity is associated with a southern shift of the Intertropical Convergence Zone and an eastward shift in the equatorial convergence zone. This reconstruction, which is based on new data from a Somali margin sediment core, is supported by previously reported tropical paleoclimatic records and suggests that global scale millennial climatic variability is in part driven by modulations in the tropical hydrological cycle and tropical emissions of the greenhouse gases \text{CH}_4 and \text{N}_2\text{O}. 

Introduction

The Arabian Sea Summer Monsoon (ASSM) winds, which flow from the coast of Somalia over the Arabian Sea to India between June and September, are a consequence of the seasonal temperature differential between the Indian Ocean and the Asian subcontinent. As the continent warms in the boreal summer a low pressure cell is created which drives moisture-laden winds onshore and results in heavy regional precipitation (Fig. 1A). During the summer months the West Coast of India receives approximately 80% of its annual rainfall (Wang et al., 1999). The southwesterly summer monsoon winds create an anti-cyclonic gyre in the Arabian Sea and generate intense upwelling off the coast of Oman, which supplies the surface waters with nutrients and supports high local productivity (Nair et al., 1989). Spring and summer dust storms over the semi-arid Arabian Peninsula region generate aerosols that are transported to the Northern Arabian Sea and dominate the marine lithogenic records in areas not directly impacted by the Indus Fan sediments (Clemens, 1998; Clemens et al., 1990; Clemens et al., 2003; Leuschner et al., 2000; Sirocko et al., 2000; Sirocko et al., 1991). In the autumn, as the Asian sub-continent cools, the winter winds become northwesterly and bring dry cool air down from the Himalayan highlands. During the winter months precipitation over India diminishes and upwelling ceases off the coast of Oman.

We are presenting data from core 905, a marine sediment core recovered in 1993 during the Netherlands Indian Ocean Project (NIOP). Core 905 was retrieved from a water depth of 1586 m, below the present day Oxygen Minimum Zone (OMZ) in the southwestern Arabian Sea near the coast of Somalia (Fig. 1) (Van Weering et al., 1997). The Somali Basin is isolated from the Arabian Basin by two oceanic ridges and the impact of the Indus River discharge at this site is negligible. This area is directly influenced by the southwesterly ASSM and experiences little to no influence from the northeasterly winter monsoon, therefore it is an ideal site from which to reconstruct summer monsoon induced coastal upwelling and the associated organic paleoproductivity (Jung et al., 2002).

Materials and Methods

The oxygen isotope record was produced using the planktonic foraminifer, Neogloboquadrina dutertrei, picked from the fraction of sediments larger than 250 µm. Measurements of stable isotopes were performed on about 5 specimens of N.
dutertrei per sample using a Finnigan MAT 252 mass spectrometer in Amsterdam. Samples were dissolved in orthophosphoric acid at 80 °C. All isotope results are given relative to the PDB standard in permil (‰). Long term reproducibility of a routinely analysed in-house CaCO₃ standard is better than about 0.09 ‰ for oxygen and about 0.05 ‰ for carbon.

Elemental concentrations were determined using a Philips PW2404 wavelength dispersive automatic sequential X-ray Fluorescence Spectrometer fitted with an Rh-anode end window X-ray tube. A 1 g sediment pellet was prepared for Ba, a glass disc (1 g sediment, 4 g flux) was used for Al determinations. The ratio Ba/Al is used to identify biogenic Barium concentrations above the average lithogenic value (ca. 60 x10⁻⁴)(Dymond et al., 1992) and to remove the effects of CaCO₃ dilution. Low values of Ba/Al suggest that lithogenic Ba is depleted in this area compared to the average lithogenic value.

Total carbon percentages were determined using a CE (NA2500) Elemental Analyzer and % inorganic carbon was measured on a Coulometrics 5012 coulometer. Percent organic carbon was obtained by the difference, with a combined precision of ± 3.9 %.

Nitrogen isotopes were determined using a CE Instruments NA2500 Elemental Analyser interfaced with a VG PRISMIII Stable Isotope Ratio Mass Spectrometer via a dual reference gas injector box and a diluter. The delta notation: \[ \delta^{15}N = \left( \frac{^{15}N/^{14}N_{\text{sample}}}{^{15}N/^{14}N_{\text{standard}}} \right) - 1 \]
is used and all values are presented as permil (‰). The standard is atmospheric nitrogen. The precision of this measurement is better than ± 0.2 ‰.

**Results and Discussion**

_Millennial-scale variability in the ASSM_

This 90 kyr reconstruction of ASSM intensity consists of multiple records of both southwestern Arabian Sea paleoproductivity and of local continental aridity. In the western Arabian Sea, the flux of organic-rich material to the sea floor is strongly correlated with the development of the summer monsoon, during which over 65% of the annual organic carbon flux to the sea floor is deposited (Nair et al., 1989). The ratio of barium to aluminium (Ba/Al) reflects the precipitation of biogenic barite in settling organic detritus (Dymond et al., 1992; Ganeshram et al., 2003) and therefore
provides a proxy of marine paleoproductivity. The Ba/Al record (Fig. 2C) is also independent of sedimentary dilution by biogenic CaCO₃, which

![Diagram](image_url)

**Figure 1.** Seasonal variations in the Intertropical Convergence Zone (ITCZ) and tropical convection patterns. **A.** The location of Somali Margin core 905 (10°46 'N; 51°57 'E) and comparative sites, Socotra Island (12°30 'N, 54° E), Hulu cave (32°30' N, 119°10' E), and Cariaco Basin (10°42.73 'N, 65°10.18 'W). Average July precipitation is indicated by the contours with darker shades reflecting heavier rainfall. Map was generated by the International Research Institute for Climate Prediction (http://iri.ldeo.columbia.edu) **B.** Average January precipitation. Darker shades indicate heavier rainfall. Changes in the ITCZ are identified by the seasonal position of the most intense rainfall.

is the major variable constituent in the 905 sediments (60-85 %). Despite variable sedimentary dilution and organic preservation effects, the record of sedimentary organic carbon (% Corg) (Fig. 2D) closely follows Ba/Al. Hence, the Ba/Al and % Corg records provide clear evidence of millennial-scale (greater than centennial but less than orbital) changes in upwelling-driven local productivity induced by the ASSM winds. The combined paleo-productivity records from the Somali margin are similar to Northern Arabian Sea productivity records (Schulz et al., 1998) and confirm that millennial changes in the organic carbon content of Arabian Sea sediments are related
to summer monsoon-driven productivity rather than differential preservation of organic matter and sedimentary dilution effects.

Today, the oxygen concentrations in the Arabian Sea between 150-1250 m water depth are less than 20 µmol/l off Somalia and near zero in the NE basin. Denitrification occurs in these O₂ depleted waters as a result of the bacterially mediated breakdown of organic matter using NO₃ as the oxidant (Altabet et al., 2002; Ganeshram et al., 2000). The by-products of denitrification, N₂ and N₂O, are lost to the atmosphere while the residual pool of available NO₃ becomes “heavy” through isotope fractionation (Brandes et al., 1998). The heavy δ¹⁵N signal generated by denitrification in the intermediate waters can be transported with an intermediate water-mass and identified at sites down current from the source (Kienast et al., 2002; Liu and Kaplan, 1989). The Arabian Sea intermediate waters are supplied from the equatorial region and Southern Ocean as well as from the outflow of the Red Sea (Schott and McCreary, 2001). Changes in the oxygen concentration of these intermediate water sources may have an influence on the degree of denitrification occurring in the Arabian Sea. However, in the sediments from core 905, changes in the denitrification record coincide with changes in productivity, determined from % C₉₅ and Ba/Al suggesting that the degradation of organic matter in the intermediate waters locally is modulating the degree of dysoxia incurred in the Oxygen Minimum Zone and therefore the intensity of denitrification. The 905 δ¹⁵N records support the conclusion of Altabet et al. (2002), that millennial scale variations in productivity and denitrification in the Arabian Sea are linked to the intensity of the ASSM winds.

The sedimentary record of lithogenic Al (% Al dry weight) from the Somali margin shows that changes in continental aridity resulted in a variable dust flux to site 905. As there are no large rivers draining nearby and local runoff is minimal even during the summer monsoon season, eolian transport is the most likely mechanism bringing lithogenic material to this site (Clemens, 1998; Clemens et al., 1990; Sirocko et al., 1991; Sirocko et al., 1989). Increases in % Al occur during periods of minimal monsoon intensity as identified by low values in the Ba/Al, % C₉₅ and δ¹⁵N records. Calculations of carbonate free elemental concentrations (not shown) indicate that sedimentary dilution by CaCO₃, the largest varying constituent of the 905 sediments, is not dominating the lithogenic records of core 905. The relationship of minimal monsoon intensity and increased dust flux is supported by % Ti, % Fe measurements.
(Fig. 2G, 3G-H) indicating that the lithogenic records, % Al, % Fe and % Ti reflect changes in the deflation of sediments from the Arabian Peninsula related to monsoon regulated variations in continental aridity.

**Figure 2.** Monsoon paleo-productivity and lithogenic records from Arabian Sea core 905 compared to changes in Greenland paleo-temperature. The Younger Dryas (YD) and Heinrich Events (H1-H6) are represented by shaded bands based on the ages provided by Elliot et al., (1998). Dansgaard-Oeschger interstadials are labelled as even numbers. A. The sedimentation rate for core 905 (see chapter 2). AMS $^{14}$C dates are used to generate the chronology prior to 40 kyr. The dashed lines identify the position of tie points to the GISP2 $\delta^{18}$O record. B. The oxygen isotope record of core 905 C Ba (ppm) normalized to % Al indicates excess, non-lithogenic Ba delivered to the sediments associated with the flux of organic matter (Dymond et al., 1992; Ganeshram et al., 2003) D. % total organic carbon E. The core 905 nitrogen isotopic record. Heavy values indicate increased denitrification F. Past changes in Greenland temperature inferred from the oxygen isotope record from GISP2 (Grootes et al., 1993). G. The variation in % Al indicates changing lithogenic concentrations in the sediment as a result of changes in continental aridity.
The age scale for core 905 is based on 24 radiocarbon (Jung et al., 2002) dates between 0-35 kyr (Fig. 2A) and is supported by the 905 δ¹⁸O (dutertrei) record (Fig. 2B), in which the transitions between Marine Isotope Stages 1-5 can be easily recognised. The conversion from AMS ¹⁴C dates to Calendar Ages of samples 25,000 years and younger was done using Calib 4.4 (Stuiver, 1998). Ages older than 25,000 were converted to Calendar Ages using the equation of Bard et al. (1993). The Western Arabian Sea modern day average reservoir age of 604 years used to correct the data (Southon et al., 2002) and the interpolation of intermediate ages was done using Analyseries (Paillard et al., 1996). Between 0-35 kyr, temperature transitions in the Greenland Ice Core Project core GISP2 and δ¹⁵N variations in the Arabian Sea record appear to be synchronous within the errors of both age models. This provides the rational for tying the 905 record to GISP2 between 35 - 90 kyrs, beyond the ability of radio carbon dating (see Chapter 3).

Millennial-scale temperature variations over Greenland, Dansgaard- Oeschger (D-O) warm interstadials and cold stadials, have been described in the GISP2 ice core for the last glacial period. The Somali margin paleoproductivity and denitrification records indicate that the ASSM intensity increased during warm interstadials and decreased intensity during cold stadials (Fig. 2). Marine paleorecords available from the northwestern (Altabet et al., 2002; Suthhof et al., 2001) and northeastern (T. Ivanochko; unpublished data) Arabian Sea concur with stadial/interstadial variability in the ASSM intensity and indicate the regional extent of this climate signal (Altabet et al., 2002; Ganeshram et al., 2000; Schulz et al., 1998). Furthermore, precipitation reconstructions using the nearby Socotra Island stalagmite δ¹⁸O record (Burns et al., 2003) and the Hulu Cave δ¹⁸O record from China (Wang et al., 2001) (Fig. 1) indicate less convective activity and a decrease in the East Asian Monsoon during stadials respectively. Both records are independently dated using ²³⁴U/²³⁰Th measurements and confirm the age model of core 905 and the timing of stadial/interstadial monsoon variations.

ASSM variability and the Intertropical Convergence Zone

The ASSM is integrated within a larger scale tropical climate system. Its onset is concurrent with the northward migration of the ITCZ (Sikka et al., 1980), the
convergence of the northeasterly and southeasterly equatorial trade winds that define a global “band” of high rainfall (convection) (Fig. 1). The site-specific location of the ITCZ reflects regional and seasonal atmospheric convection patterns as the latitudinal solar insolation maximum shifts between the Northern and Southern Hemispheres. Today the ITCZ reaches its northern most position, approximately 20 °N over Asia and 10 °N over South America in boreal summer (Fig. 1A). During boreal winter, the ITCZ approaches 10 °S over Asia and 3-5 °N over South America (Fig. 1B). When the ITCZ over Asia remains close to or south of the equator during boreal summer the strength of the ASSM is reduced (Joseph et al., 1994).

In the Cariaco Basin, at the northern extent of the South American ITCZ seasonal migration (Fig. 1A), downcore % Ti and % Fe measurements register millennial-scale variation in the ITCZ position (Peterson et al., 2000). Interstadials are characterized by a northerly position of the ITCZ and high local terrestrial runoff, while stadials are associated with a decrease in terrestrial input and a more southerly ITCZ position (Fig. 3B). In contrast, at the southern extension of the ITCZ migration, lake Junin (11 °S) and Lake Titicaca (16 °S) both experienced higher rainfall during the deglacial period (Seltzer et al., 2002). Drilling of the Salar de Uyuni on the Bolivian Altiplano (20°S) has exposed a sequence of diatomaceous lake sediment interdigitated with evaporative salt deposits. Radiocarbon dating of these paleo-lakes has defined wet periods (~30% more precipitation than today) during the LGM and periodically between 30-50kyr (Baker et al., 2001). Similarly, North-South antiphasing of precipitation patterns occurs in Andean ice cores; Sajama (18 °S) was cold and wet when Huscarian (9°S) was warm and dry indicating millennial-scale shifts in the ITCZ (Thompson et al., 1998). Thus these rainfall records from S. Hemisphere sites concur with a southward migration of the ITCZ during stadials.

Together, the Asian and the South American paleoclimate records illuminate a relationship between millennial-scale oscillations in the ASSM intensity and position of the ITCZ. During interstadials, the rainfall at 10°N over South America and up to 30 °N over Asia increased as the ITCZ shifted to a northern position. Conversely, during stadials the intensity of the ASSM and the rainfall over Hulu Cave, Socotra Island and the Cariaco basin decreased and precipitation over the Bolivian Altiplano, Lake Junin and Lake Titicaca increased as the ITCZ progressed to a more southern position. Therefore when the Somali margin ASSM record is compared to additional tropical climate records, evidence consolidates for the global scale rearrangement of
tropical convection in concert with stadial/interstadial oscillations. We submit that the comparison of these paleoclimatic records allows the individual sites to be placed in the larger context of millennial-scale climate change and shows that the tropics as a whole are an indisputable factor in global climate change.

Figure 3. A comparison of tropical climate records and atmospheric greenhouse gas concentrations for the past 90 kyr. The Younger Dryas (YD) and Heinrich Events (H1-6) are indicated by shaded bands. A. The $\delta^{18}O$ 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 (Peterson 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) (Sowers et
ASSM, ITCZ and El Niño/Southern Oscillation

The El Niño/Southern Oscillation (ENSO) is also associated with variations in the ASSM (Joseph et al., 1994; Ju et al., 1995; Krishnamurthy et al., 2003; Sikka et al., 1980). The relaxation of the equatorial trade winds during an El Niño year removes the forcing that concentrates warm waters in the Western Equatorial Pacific (WEP) and brings cold waters to the surface in the Eastern Equatorial Pacific (EEP). As the WEP warm pool relaxes back along the equator towards the Americas and the EEP “cold tongue” dissipates, the Asian low-pressure system moves eastwards. In response to the replacement of the EEP cold tongue with warmer surface waters, the ITCZ moves south over South America. The eastward shift of the low-pressure center also disperses the Asian Low that initiates the ASSM.

Charles et al (1997) provide evidence from tropical corals (Charles et al., 1997) which indicates that this relationship between ENSO and the ASSM has held over the past two centuries. Therefore the question arises that has recently sparked a debate in the literature (Rosenthal et al., 2004): Has the integrity of the ASSM-ITCZ-ENSO relationship been retained during millennial-scale oscillations? A comparison between Equatorial Pacific records and the 905 records indicate that the answer is yes. High-resolution $\delta^{18}O$ measurements from the eastern Indonesian Archipelago (Stott et al., 2002) suggest that low salinities, which occur today during La Niña events, dominated during interstadials, while stadials are associated with high salinity conditions similar to modern El Niño conditions. The stadial/interstadial variations in WEP salinity, ASSM intensity and ITCZ position indicate that an eastward shift in the Pacific convection zone coincided with low monsoon rainfall and a southern position of the ITCZ. Conversely, an intense WEP warm pool coincides with high monsoon rainfall and a northern position of the ITCZ. As ENSO variations have global
repercussions, we propose that these coherent stadial/interstadial rearrangements of the tropical convection centers have influenced the global climate.

*The global consequences of variations in tropical convection*

Paleo-evidence for stadial/interstadial reconfiguration of the tropical climate system, provides crucial insight into the feedbacks that amplify and perpetuate rapid climate oscillations. The addition of water vapour to the atmosphere affects global temperature both as a greenhouse gas and as a mechanism of latent heat transport from the subtropics to the high latitudes (Pierrehumbert, 2000). Contracting and expanding the regions of subtropical convection dramatically changes the humidity of the tropics and therefore tropical temperatures (Pierrehumbert, 1999). During El Niño events, both the temperature of the tropics and the average global temperature increase however, temperature of the high latitudes decrease. Consequently, the temperature gradient between the tropics and polar regions is enhanced during El Niño events (Kukla et al., 2002). Kukla et al (2002) indicate that the frequency of El Niño events increases when the seasonal cycle is amplified and present model results which show that more El Niño events occur during glacial periods than during interglacial periods. We suggest that southward shifts of the ITCZ during stadials were accompanied by reduced tropical convection. This would lead to a net decrease in both atmospheric water vapour and the northward penetration of latent heat: conditions analogous to those documented during an El Niño year in the Pacific (Pierrehumbert, 1999).

Further evidence for an overall reduction in tropical moisture during stadials is provided by ice core CH₄ records (Fig. 3C-D). Global wetland areas are the largest single source of methane emissions and contribute 115-237 Tg CH₄ / yr to the atmosphere, 50-70 % of which is from tropical wetlands (IPCC 2001). The variation in atmospheric methane concentration is highly correlated with precessional insolation changes (Chappellaz et al., 1993) as observed in monsoon paleo-records (Clemens et al., 2003; Leuschner et al., 2003)(and references therein). On a millennial-scale, the relationship between ASSM variation and atmospheric CH₄ concentration appears robust, with increases in the ASSM strength during interstadials coinciding with increases in atmospheric CH₄ (Fig. 3C-D). Decreases in atmospheric CH₄ during stadials, periods of weak monsoonal precipitation and high tropical aridity, highlight the tropics as a probable regulator of atmospheric greenhouse gas emissions on a millennial-scale. The close agreement between the 905 dust records
(Fig. 3G) and those from both Greenland and Antarctica (Fig. 3H) show that glacial periods and stadials are dustier than interstadials. Increased aridity during cold periods is also inferred from loess deposits (Porter et al., 1995) which provide further evidence of a global net decline in tropical moisture sources during these periods. Therefore, the dust and CH$_4$ records further reinforce the argument for a positive feedback through tropical water vapour and provide mechanisms for greenhouse amplification of millennial climate changes.

Ice core records of nitrous oxide (N$_2$O) show millennial-scale fluctuations that are broadly similar to CH$_4$ (Flückiger et al., 2004; Flückiger et al., 1999; Sowers et al., 2003) (Fig. 3E). Nitrification and denitrification both produce N$_2$O as a by-product, consequently terrestrial wetlands (Sowers et al., 2003) and marine upwelling areas (de Wilde et al., 1997; Naqvi et al., 1998) dominate the non-stratospheric sources of N$_2$O. The nitrogen and oxygen isotope signatures of atmospheric N$_2$O suggest that the ratios of terrestrial to marine N$_2$O sources have remained fairly constant throughout the last 33 ky (Sowers et al., 2003). The mechanism that links the marine and terrestrial N$_2$O sources requires an explanation. The Arabian Sea denitrification record (Fig. 3F) resembles the low resolution GISP2 N$_2$O record as well as the discrete high-resolution records of the Greenland Ice Core Project (GRIP) and North GRIP (Fig. 3E). Given that the $\delta^{15}$N record reflects denitrification changes in the ocean that result from variable monsoon winds which determine the rainfall over the Indian subcontinent, then the link between marine and terrestrial N$_2$O emissions is apparent. We suggest that the areal extent of wetlands (the terrestrial N$_2$O source) and the oceanic denitrification rates varied in tandem both responding to the strength of the monsoon and the rearrangement of tropical convection patterns.

The tropical climate interactions proposed here provide 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 millennial time-scales. Through greenhouse gas feedbacks, rearrangement of low-latitude convection patterns could amplify and perpetuate millennial-scale climate changes. We suggest that transitions in the integrated ASSM-ITCZ-ENSO tropical climate system hold the key to persistent rapid climate changes that are evident in the paleo-records.
References:


Kienast, S.S., Calvert, S.E., Pedersen, T.F. Nitrogen Isotope and productivity variations along the northeast Pacific margin over the last 120 kyr: Surface and subsurface paleoceanography. Paleoceanography 17(4): art no. 1055, 2002.


