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Monsoon Could Trigger the Global Abrupt Climate Changes: New Evidence from the Bay of Bengal

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ABSTRACT
In recent years evidence has been pouring in mainly from marine records, supporting the hypotheses that temperature changes in the Arctic and Greenland steer the intensity of the Asian Monsoon (Schulz et al., 1998; Kudrass et al., 2001; Gupta et al., 2003; Wang et al., 2001). However, the physical link between the high latitude climate and monsoons are still elusive. Here we use oxygen isotopes and Mg/Ca data of planktonic foraminifera species (Globigerinoides ruber) from a sediment core in the Bay of Bengal to reconstruct sea surface temperature (SST) and surface water oxygen isotopic values. We find that oxygen isotopic values (monsoon signal) and SST of the Bay of Bengal (BOB) lead the Dansgaard-Oeschger (D-O) events. We, therefore suggest that the monsoon could kick the start of millennial scale abrupt climate changes through the shifts of the Intertropical Convergence Zone (ITCZ) and associated convection, water vapor supply to the tropical troposphere and latent heat penetration.

Key words: Monsoon, climate change, oxygen isotopes, planktonic foraminifera species, sea surface temperature, Dansgaard-Oeschger (D-O) events, Intertropical Convergence Zone (ITCZ).

INTRODUCTION

The Indian monsoon is an important component of global climate transporting heat and moisture from the warmest part of the tropical ocean across the equator and to higher latitudes. Seasonal reversals of monsoon winds and associated monsoon rainfall over Asia have a direct effect on the socio-economic and agricultural development in the densely populated Asian region. Monsoon reconstructions based on proxies such as Globigerina bulloides abundances (Gupta et al., 2003), total organic carbon records (Schulz et al., 1998) from marine sediment cores from the Arabian Sea and oxygen isotopic ratios of speleothem deposits from Oman (Fleitman et al., 2003) and China (Wang et al., 2001) have demonstrated that abrupt changes in monsoon intensity coincide with temperature changes indicated in the Greenland GISP2 ice core record. Such kind of coherent changes between monsoon and high latitude climate records prompted to link the monsoon changes to the North Atlantic and/or Greenland temperature changes (Schulz et al., 1998; Kudrass et al., 2001; Gupta et al., 2003). Similarly, synchronous occurrences of Dansgaard-Oeschger (D-O) events in the tropical Atlantic Ocean and South America (Jennerjahn et al., 2004; Wang et al., 2004) and in the equatorial Pacific (Kienast et al., 2006) were documented.

Martin et al., (1981) have indicated that the four major rivers Irrawaddy, Brahmaputra, Ganges and Godavari discharge annually approximately $1.5 \times 10^{12} m^3$ of fresh water into the Bay of Bengal (BOB). In addition annual rainfall over the bay varies between 1 m off the east coast of India to more than 3 m in the Andaman (Baumgartner and Reichel, 1975). The peak discharge of rivers and rainfall over the bay occurs during the SW monsoon season, which leads to a strongly stratified near-surface layer. Therefore, the salinity variations and oxygen isotopic values of surface water ($\delta^{18}O_{SW}$) of the BOB on interannual and longer time scales are strongly controlled by SW monsoon rainfall. Therefore, we investigate the SST and $\delta^{18}O_{SW}$ changes of the BOB at the millennial time scale for the last 33 kyr to determine: i) the past variability of the local salinity to infer changes in the monsoon precipitation ii) how variability of the fresh water flux and ocean dynamics of the Bay of Bengal was related to the high latitude climate changes.

Material and Methods

Core SK-218/1 was collected at a water depth of 3307 m from the BOB (14°02′06″ N; 82°00′12″ E), this location experiences more than 2000 mm of annual rainfall, primarily during the summer monsoon season. The site location is characterized by moderate rates of sediment accumulation throughout over last 60 kyr. The age model for the last 37 kyr is based on the AMS carbon 14 dates determined on the species Globigerinoides ruber. The measured ^{14}C ages were converted to sediment ages using the online CalPal version quickcal 2005 ver1.4 (Weninger et al., 2006) routine with a marine reservoir correction of 400 years. The chronology is extended further by correlating $\delta^{18}O$ of G. ruber to the low latitude isotopic stack chronology of Martinson et al., (1987). The time scale was constructed assuming constant sedimentation rates between radiocarbon dates and isotope tie points. On the basis of this model, the average sample spacing is 500 years. The sediment accumulation rate varies significantly from 6 to 18 cm/kyr between the Holocene and the glacial period.

For determination of Mg/Ca, for each sample 30 to 40 individuals of Globigerinoides ruber (white variety) with a size range of 250 to 350μm were picked. The picked specimens were then cleaned following the procedure of Barker et al., (2003). Splits of the cleaned samples were digested in diluted HNO_3 and analyzed for Mg and Ca on a ThermoFinnigan Element2 sector field inductively coupled plasma mass spectrometer. Elemental concentrations were derived from the isotopes ^{25}Mg and ^{43}Ca; ^{89}Y served as internal standard. The analytical errors for the Mg and Ca concentrations were better than 0.7% relative standard deviation (RSD). 40 sample solutions were measured in replicate, and the repeatability for Mg/Ca was routinely better than -0.1 mmol/mol. This translates to an uncertainty of about ±0.2 °C in the reconstructed SST.

For δ^{18}O of calcite a split of the cleaned foraminifers were loaded in a stainless steel boat, an automated sample carousel, for sequential acidification online. The CO_2 evolved in the reaction was transferred to the inlet of a gas ratios table isotope mass spectrometer using cryogenically routine procedures and the sample gas was compared to an internal standard gas sequentially 10 times. The difference in the ^{18}O/^{16}O of the sample and the internal standard is reported in the delta (δ^{18}O) notation relative to the PDB standard. Our routine precision of δ^{18}O for standards run in conjunction with samples averaged ~0.10‰ over the course of the present study. By subtracting the Mg/Ca-derived temperature component from δ^{18}Oc, we obtained $\delta^{18}O_{SW}$. $\delta^{18}O_{sw}$, in turn, is linearly correlated with salinity; the modern slope for the Bay of Bengal is 0.18 ‰ per psu (Delaygue et al., 2001). Further, $\delta^{18}O_{SW}$ and SST at this site show an insignificant relationship (r=-0.32).This also suggests that dilution plays a major role in controlling the salinity variation. After the removal of global $\delta^{18}O_{SW}$ linked to ice volume and sea level changes (Shackleton, 2000), the fluctuation in δ^{18}Osw of the BOB essentially serves as a proxy of rainfall and river runoff, both are strongly coupled to the summer monsoon. Hence we will interpret changes in δ^{18}Osw in the BOB core solely as a monsoon signal.

RESULTS AND DISCUSSION

Synchronous $\delta^{18}O_C$ Changes

For the time period from 12 to 65 kyr the foraminiferal δ^{18}O record from the BOB shows striking similarities with the GISP2 ice core δ^{18}O record, which essentially represents changes of air temperature in the high latitudes of the northern hemisphere (Dansgaard et al., 1993). However, from 12 kyr to present day the BOB $\delta^{18}O_C$ record is more variable compared to the Globigerinoides ruber (GISP2) δ^{18}O record (Figure 1). The BOB $\delta^{18}O_C$ record exhibits minima corresponding to the Dansgaard-Oeschger (D-O) events 1,3,5,6,7,8,9,10,12,14,15 and 16, suggesting that whenever the temperatures were warmer (interstadials) in Greenland, the BOB was less saline. This observation is in line with several other studies from the Arabian Sea (Schulz et al., 1998) and the Bay of Bengal (Kudrass et al., 2001) and speleothem records from Hulu Cave, China (Wang et al., 2001). However, two factors can contribute to the lighter δ^{18}O values in foraminifera; warm calcification temperatures as well as lower $\delta^{18}O_{sw}$.

The SK-218/1 δ^{18}Oc record does exhibit a few differences compared to the GISP2 record: the D-O events 2 and 4 and the Younger Dryas event lead by 1 kyr. To isolate precipitation and river-run off, which are strongly associated with monsoon rainfall in this region (i. e. monsoon signal), we have compared δ^{18}Osw with the D-O events documented in the GISP2 record for the period where we have a good control on the chronology of the BOB core and GISP2 record.

The mean δ^{18}Oc difference between the Holocene and last glacial maximum is about 2.1‰ after removing the global ice volume effect of 1.2‰. The remaining 0.86‰ reflects temperature and salinity changes. The 2°C temperature change between Last Glacial Maximum (LGM) and Holocene (Figure 1) accounts for 0.48‰, remaining 0.38‰ indicates that salinity was ~2 psu higher in the Bay of Bengal during the LGM, with more evaporation and less precipitation. Although the NE monsoon activity was stronger during the LGM (Duplessy, 1982), this did not lower the salinity considerably in the BOB. However, one could see the difference in salinity gradient between the Arabian Sea and BOB during LGM which is attributable to the cause of NE monsoon during LGM.

δ^{18}Osw, SST and D-O Events:

The δ^{18}Osw in the BOB shows D-O events 1, 2, 3 and 4 very prominently with shifts of 0.54‰, 0.31‰, 0.37‰ and 0.55‰ respectively, but the timings of the $\delta^{18}O_{SW}$ shifts (events) differ as compared to the GISP2 data set, all four events in the BOB record lead the D-O events as recorded in the GIPS2 core (Figure 2). Similarly, BOB SST changes in particular at Heinrich Events, during deglaciation and at D-O events 1, 2, 3, and 4 lead the GISP2 δ^{18}O record (Figure 2). More strikingly, the deglacial warming in the BOB started between 17 to 18 kyr (Figure 3), leading the warming of the high latitudes by 2-3 kyr. Similarly, other well-dated cores from the Arabian Sea show an early deglacial warming (Sirocko et al., 1993; Peeters et al., 1999). We realize that the robustness of the

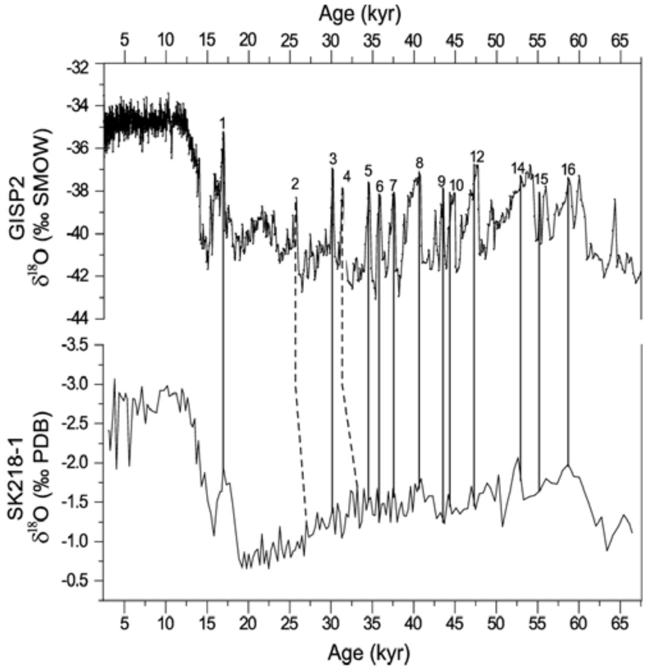

Figure 1. Oxygen isotopic values of Globigerinoides ruber ($\delta^{18}O_C$) from a SK-218/1 sediment core from the Bay of Bengal and GISP2 $\delta^{18}O$ record data plotted as a function of age. The chronologies of SK218-1 and GISP2 are independent. The vertical dotted lines represent synchronous changes in oxygen isotopic values during Dansgaard-Oeschger (D-O) cycles between these two records.

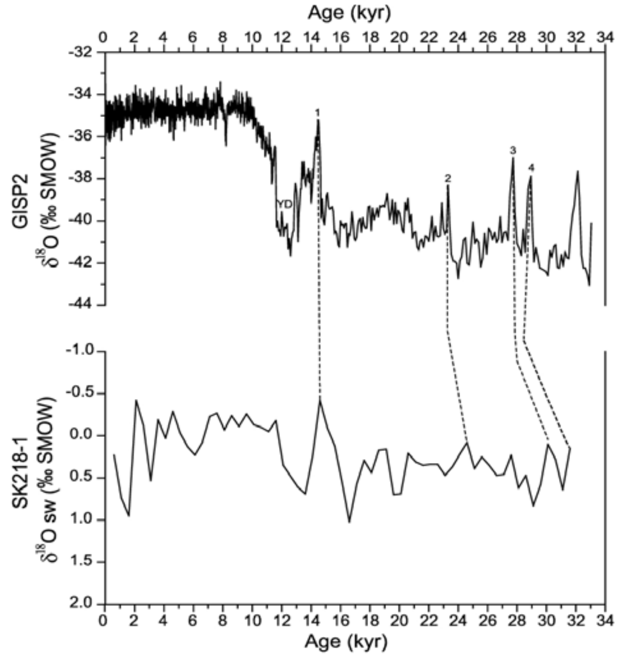

Figure 2. Oxygen isotopic values of waters ($\delta^{18}O_{SW}$) from the Bay of Bengal and oxygen isotopic values of GISP2 ice core plotted as a function of age. The abrupt changes in $\delta^{18}O_{SW}$ at YD, D-O Event 1, 2, 3, and 4 lead the similar changes in GISP2 Ice core. YD: Younger Dryas.

comparison of the BOB $\delta^{18}O_{SW}$ and SST records with the GISP2 $\delta^{18}O$ record depend on the synchronization of age scales. The age model of the BOB core (SK218/1) does not have sub-millennial precision. However, the lead of SST and $\delta^{18}O_{sw}$ versus air temperature by 600 to 1000 years is persistent throughout the record. It is this persistence that gives us the confidence to interpret the lead as true environmental signal and not as artifact or random result due to limitations of the age model.

Our record of $\delta^{18}O_{SW}$, which is a more reliable proxy of monsoon rainfall than the other marine proxies used so far in the northern Indian Ocean (Schulz et al., 1998; Kudrass et al., 2001) show an apparent lead over the D1, D2, D3 and D4 of the GISP2 $\delta^{18}O$ record. Not only the $\delta^{18}O_{SW}$ but also the SST shows a clear lead over the GISP2 $\delta^{18}O$ record. Similarly, equatorial Pacific (Lea et al., 2000), Sulu Sea (Rosenthal et al., 2000) and equatorial Indian Ocean SST records (Saraswat et al., 2005) also show a lead over the global ice volume curve. Accordingly, the lead of tropical Pacific and Indian Ocean temperatures appears to be a robust feature. Therefore, we suggest that abrupt climate shifts such as the D-O events have first occurred in the monsoon-influenced regions and later in the northern hemisphere high latitudes.

Role of monsoon in triggering D-O events

It was proposed that fresh water input to the North Atlantic would initiate thermohaline circulation changes responsible for abrupt climate shifts during the last glaciation (Clark et al., 2001). Nevertheless, model simulations do not provide compelling proof to support the role of thermohaline circulation changes in governing the abrupt climate shifts on the global scale (Broecker, 2003). Accordingly, the mechanism by which thermohaline circulation changes of the North Atlantic will propagate the abrupt climate changes to the tropics in general, and monsoon changes, in particular, are not clear yet. We, therefore, invoke a role of the monsoon, which could propagate the signal from the tropics to high latitudes through tropical convection.

During Boreal Summer, the ITCZ migrates northward across the Indian Ocean and the Indian subcontinent, bringing with it summer monsoon rainfall (Gadgil, 2003). The Asian monsoon plays a dominant role in the tropical climate because it transports heat and moisture from the warmest part of the tropical ocean across the equator and to the high latitudes. The addition of water vapor to the atmosphere affects temperature both as a greenhouse gas and as a mechanism of latent heat transport from the

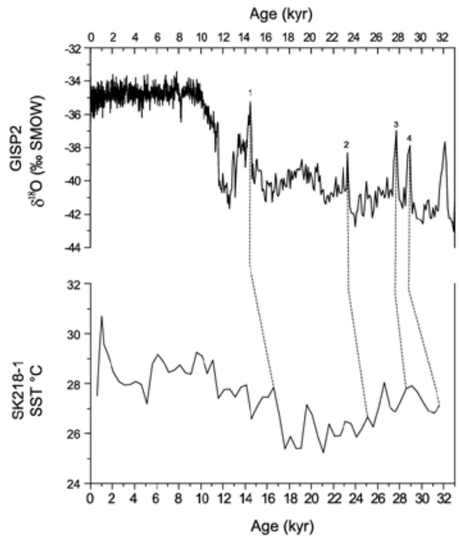

Figure 3. Sea surface temperatures variations in Bay of Bengal and oxygen isotopic variations of GISP2 ice core plotted as a function of age. Sea surface temperatures in the Bay of Bengal (calculated from Mg/Ca) lead the Greenland air temperatures indicated by ice $\delta^{18}O$.

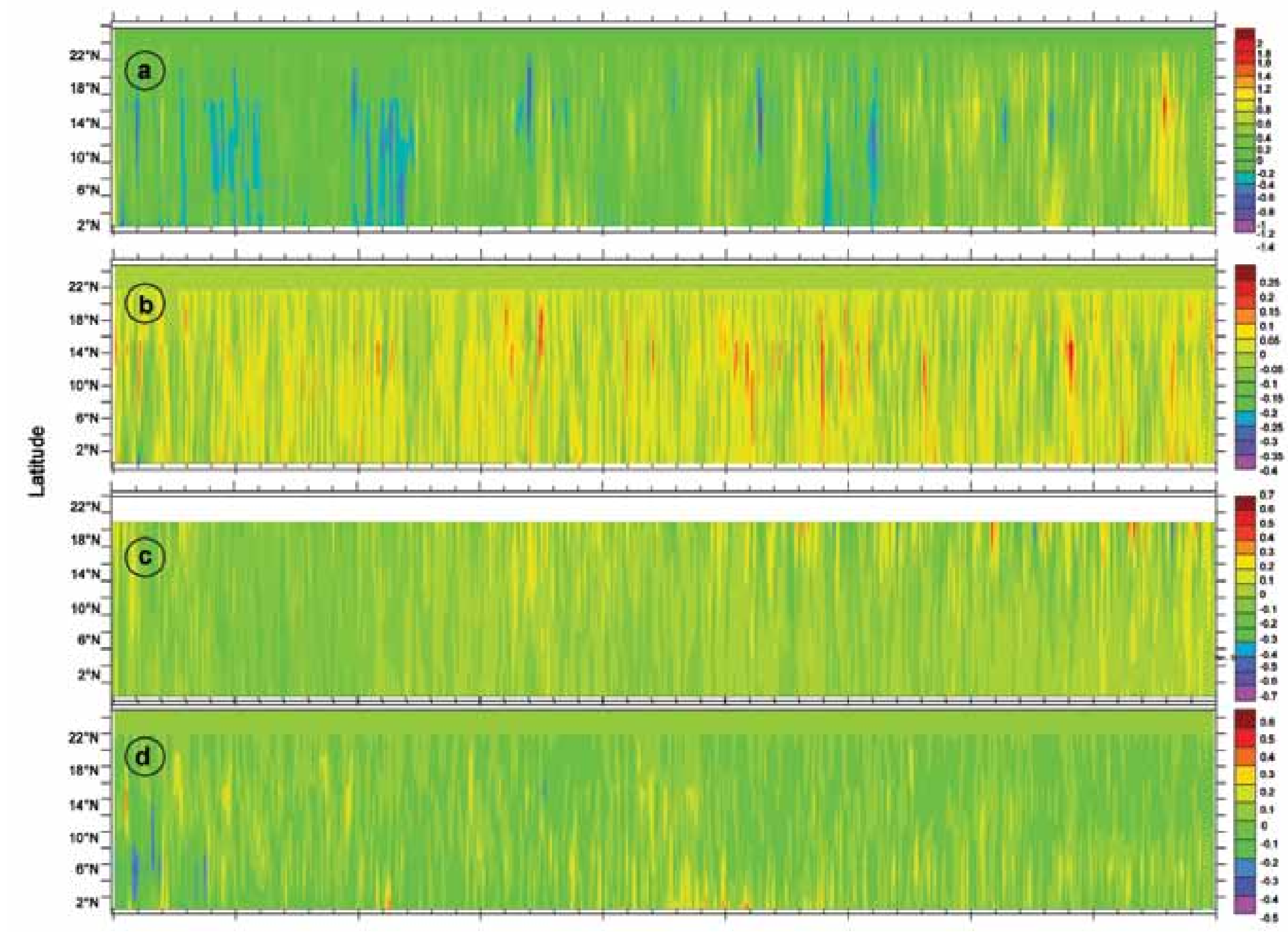

Figure 4. Instrumental data set obtained from Wooodruff et al., (1987), for the years from 1945 to 1985, anomalies of (a) SST, (b) cloudiness (ITCZ), (c) evaporation (latent heat) and (d) rainfall.

Table 1. Chronological tie points with reference to depth in the Core SK 218-/1 from the Bay of Bengal. 0 to 66 cm sediment contains slumped material from the slope indicated by an age reversal. Below 68 cm the sediment is undisturbed.

Depth (cm)	C^{14} Ages (in years)	Calendar Age (in kyr BP)
68	1055+60	0.62
266	10400+60	11.51
322	13940+90	16.81
638	33060+90	37.10
742	3.3 event	50.51*
794	4/5 boundary	58.96*

tropics to high latitudes. During interstadials (D-O events 1, 2, 3 and 4) the ITCZ had moved further north which increases the tropical convection, resulting in an increase in overall tropical humidity and consequently an increase in the temperature of the tropics. As a consequence of air temperature rise in the Asian region ice melts on the Tibet Plateau, decreases the albedo in the region, increasing the pressure gradient between the Indian Ocean and the Tibet Plateau. This kind of set-up accelerates the monsoon circulation and precipitation over the Indian subcontinent. As the position of the ITCZ shifts away from the equator during the monsoon season the mass energy transport carried by the Hadley cell intensifies (Lindzen and Hou, 1988). Such intensification enhances the water vapor supply to the tropical troposphere, which affects the mean tropical SST (Seager et al., 1988). Tropics in general and the Indo-Pacific warm pool in particular are the main regions from which water vapors are supplied to the atmosphere. As the water vapor is one of the main greenhouse gases, its substantial variation in the atmosphere directly affects the SST in the region.

The global atmosphere is very sensitive to changes in tropical SST (Pierrehumbert, 2000) and SST changes in the tropics must initiate feedbacks that alter the energy budget of the planet, which in turn affect climate over much of the globe through changes in the stationary wave pattern (Trenberth et al., 1998). Further, tropical convection could reorganize in a way to shift the ITCZ, either through autonomous variability of the coupled atmosphere-ocean system or in response to orbital changes in the insolation pattern. The propensity for convection increases with SST, and there is a threshold value of SST of about 27.5°C for the Indian Ocean, above which convection increases (Gadgil, 2003). Thus, if the SST of the BOB exceeds 27.5 °C, as a result, the co-variation between SST and precipitation in the tropical Indian Ocean increases. A contraction and expansion of the tropical convection region can decrease and increase temperature, respectively in the tropics (Pierrehumbert, 2000). Further, a decrease in Asian monsoon activity during stadials was related to less convective activity in the monsoon regions (Wang et al., 2001), which supports the concept that tropical convection and monsoon strength are related

In this contexts, we have analyzed SST, cloudiness (ITCZ), evaporation (latent heat) and rainfall for the years from 1945 to 1985. During the active monsoon years, 1961, 1970, 1975, 1983 and 1988 a strong coupling among the ITCZ propagation and rate of evaporation and precipitation is found (Figure 4). Thus, high energy of the tropics and the associated hydrological cycle of the monsoon system itself have a scope for reorganization that could lead to rapid climate transitions. Therefore, SST and $\delta^{18}O_{SW}$ changes in the BOB lead the D-O events in the high-latitude North Atlantic during the past 30 kyr.

It was pointed out earlier that the tropical Pacific is actively involved in forcing global climate change because the tropical Pacific serves as a heat engine for earth's climate and as a vapor source of its hydrological cycle (Lea et al., 2001; Clement et al., 1999; Visser et al., 2003). On the other hand, it is now evident that the Indian Ocean plays an active role in controlling the SST in other parts of the tropics including the Pacific (Cobb and Charles, 2001). Further, Indian Ocean SST anomalies peak 2-3 years prior to those in the Pacific and maximum Indian Ocean anomalies occur at a time when the external forcing from tropical Pacific SST is minimum (Cobb and Charles, 2001). Thus, monsoonal processes in the Indian Ocean should exert considerable influence over the climate variability of both the tropical and mid-latitudes.

A teleconnection mechanism through the Pacific El Niño system was invoked to explain synchronous changes between monsoon records from the Arabian Sea and northern hemisphere high latitude records (Sirocko et al., 1996). However, linking the monsoon changes to El Niño is rather complex, because during the ENSO initiation phase (June – August), for example, Arabian Sea summer monsoon winds are weakened while those in the South China Sea are strengthened. In contrast, during the mature phase of ENSO (December- February) South China Sea winter monsoon winds are significantly weakened while the Arabian Sea winter monsoon winds are only slightly weakened (Wang et al., 2003).

Long-term rainfall variations in China (Wang et al., 2005) and Oman (Neff et al., 2001) appear to follow summer insolation changes. Similarly, temperature changes in the North Atlantic also show a similarity with solar insolation changes (Bond et al., 2001). Such kind of synchronous shifts in high latitude climate and tropical monsoon, and their overall trends matching solar insolation changes suggest that the foot-print of solar impact on climate extended from polar to tropical latitudes. In the tropics the solar insolation is predominantly tied to the precession cycle of the Earth's orbit (Berger and Loutre, 1991), the monsoon changes occurred in close association with the harmonic tones of Earth's precessional cycle (23 kyr) (Sirocko et al., 1996). Hence, the precession cycle of variation in solar insolation, water vapor, convection, ITCZ movement in the tropics and the strong tropical ocean-atmosphere feedbacks (Wang et al., 2001; Ivancho et al., 2006) could initiate and enforce the millennial-scale abrupt climate changes on the global scale.

CONCLUSION

The primary implication of this study lies in monsoon and associated water vapor of the tropics. It is evident that the linkage between monsoon and associated water vapor of the tropics has a strong bearing on the tropical SST and convection. Both monsoon changes and tropical convection can be forced by the solar insolation changes caused by the precession cycle, which would trigger the abrupt climate changes noticed in the northern hemisphere high latitudes. As such, primary lead of monsoon signal over the northern hemisphere high latitude climate strongly supports the notion that the tropics are actively involved in forcing abrupt climate changes on the global scale, but such kind of tropical forcing mediated through monsoons.

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Compliance with Ethical Standards

The authors declare that they have no conflict of interest and adhere to copyright norms.

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