Palaeogeography, Palaeoclimatology, Palaeoecology 446 (2016) 11–18

Contents lists available at ScienceDirect

Palaeogeography, Palaeoclimatology, Palaeoecology

journal homepage: www.elsevier.com/locate/palaeo

North Atlantic climatic changes reflected in the Late Quaternary foraminiferal abundance record of the Andaman Sea, north-eastern Indian Ocean

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ARTICLE INFO

Article history:
Received 3 June 2015
Received in revised form 28 December 2015
Accepted 6 January 2016
Available online 14 January 2016

Keywords:
Globigerina rubescens
Neogloboquadrina dutertrei
Dansgaard-Oeschger events
Heinrich events
Andaman Sea
North Atlantic

ABSTRACT

Here, we present planktonic foraminiferal, benthic foraminiferal and other proxy profiles from well-dated sediment cores in the Andaman Sea showing changes in climate and oceanography at Dansgaard-Oeschger (D/O) and Heinrich scales. The large temporal variations in the abundances of total benthic foraminifera, *Globigerina rubescens* and *Neogloboquadrina dutertrei* suggest substantial changes in the surface to bottom hydrography of the Andaman Sea. *G. rubescens* abundance minima during the last glacial cycle correspond to warm interstadials (D/O events 1 to 14) while maxima correspond to Heinrich events (H1 to H4), the last glacial maximum (LGM) and the Younger Dryas. D/O events are marked by very low *G. rubescens* and high *N. dutertrei* abundances which indicate freshened surface water related to increased direct precipitation (over evaporation) and strengthened Irrawaddy outflow. Lower abundance of *N. dutertrei* (and higher abundance of *G. rubescens*) during North Atlantic Heinrich events, the deglacial, the YD and the mid- to late-Holocene reflect reduced influx of fresh water as a result of weakened summer monsoon freshwater input. The timing of these Andaman Sea monsoonal changes indicate a strong teleconnection to North Atlantic climate change.

1. Introduction

Dansgaard-Oeschger (D/O), Bond and Heinrich events associated with Northern Hemisphere glacial climates during the late Quaternary were first identified in marine records of the Atlantic Ocean (Bender et al., 1994; Bond et al., 1992, 1997; Heinrich, 1988) and later in the distant regions such as China (Wang et al., 2001), Santa Barbara Basin (Behl and Kennett, 1996; Hendy and Kennett, 2000), Arabian Sea (Burns et al., 2003), Bay of Bengal (BoB) (Kudrass et al., 2001; Marzin et al., 2013) and Andaman Sea magnetic records (Colin et al., 1998). The records from the BoB, Santa Barbara basin and China demonstrate a strong link between the East Asian monsoon and the North Atlantic climate for the last glacial period (Dykoski et al., 2005). These rapid changes also correlate to high-amplitude climatic changes inferred from $\delta^{18}O$ records of Greenland ice cores and are believed to be driven via atmospheric and or oceanic teleconnection (Zonneveld et al., 1997). The study by Bond et al. (2001) also shows that these glacial climatic fluctuations extend in to the Holocene.

The impact of the North Atlantic climate changes on larger Asian monsoon systems has gained wide attention. Studies show that enhanced summer monsoons were coincident with interstadial D/O events whereas weak monsoons were coincident with Heinrich events of the North Atlantic (Sirocko et al., 1996; Schulz et al., 1998). Thus, recent focus has been on understanding the relationship between North Atlantic rapid climate change and the Indian monsoon and to infer the mechanisms responsible for the linkages.

An atmospheric teleconnection with the eastern and central North Pacific and an atmosphere–ocean interaction in the tropical North Pacific are also thought to play a key role in modulating the strength of the Indian monsoon (Lu and Dong, 2008). At the same time, Zhang and Delworth (2005) analysed the tropical response to a weakened Atlantic Meridional Overturning circulation (AMOC) and suggested that the Indian monsoon is weakened due to a weakening of the Walker circulation in the southern tropical Pacific. Modelling studies suggest that the Asian monsoon circulation is weakened during the Heinrich events of the last glacial cycle (Jin et al., 2007). Goswami et al. (2006); Feng and Hu (2008) demonstrate a link between North Atlantic surface temperature and Indian monsoon intensity through a physical mechanism affecting the meridional gradient of upper tropospheric temperature between the Tibetan Plateau and the tropical Indian Ocean. Marzin et al. (2013) shows that the events of high salinity are associated with weak Indian monsoon circulation during cold events in the North Atlantic and Arctic. The mechanism involves increased freshwater flux in the North Atlantic, which results in a reduction of the AMOC intensity. With

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http://dx.doi.org/10.1016/j.palaeo.2016.01.009
0031-0182/

the weakening of AMOC, there is a simultaneous cooling of the Indian subcontinent (northern part) which is believed to be the causative factor for the weakening of the Indian Monsoon (Marzin et al., 2013).

In the last decade, substantial research has been carried out to better understand the impact of North Atlantic rapid climate changes on the climate of distant basins (Jin et al., 2007; Wang et al., 2001; Hendy and Kennett, 2000). There are number of isotopic and magnetic proxy records indicating rapid changes during last glacial cycle in response to the North Atlantic climate events, but there is limited data based on faunal changes from the north-eastern Indian Ocean. A large hydrological perturbation at a millennial timescale comparable to the North Atlantic was inferred from the isotopic record from the northern BoB (Kudrass et al., 2001; Marzin et al., 2013). But their inferences are mainly based on oxygen isotope records.

Our intention is to study the response of planktonic and benthic foraminifera of Andaman Sea to rapid climatic events of the North Atlantic. We employed the abundance variations of *Globigerina rubescens*, *Neogloboquadrina dutertrei* and total benthic foraminifera to evaluate potential links between the North Atlantic surface temperature and monsoon climate during the last glacial period. We used temporal changes in the abundances of *G. rubescens* (indicator of cold climate) and *N. dutertrei* (freshwater runoff and resultant low salinity) as a proxy for understanding the variability of the Indian Ocean monsoon and found large salinity variations recorded in a sediment core raised from the Alcock Seamount Complex (close proximity to Irrawaddy) and two cores from the central and southern Andaman Sea. At present, the northern core location is influenced by freshwater discharge from the Irrawaddy and Salween rivers (Fig. 1).

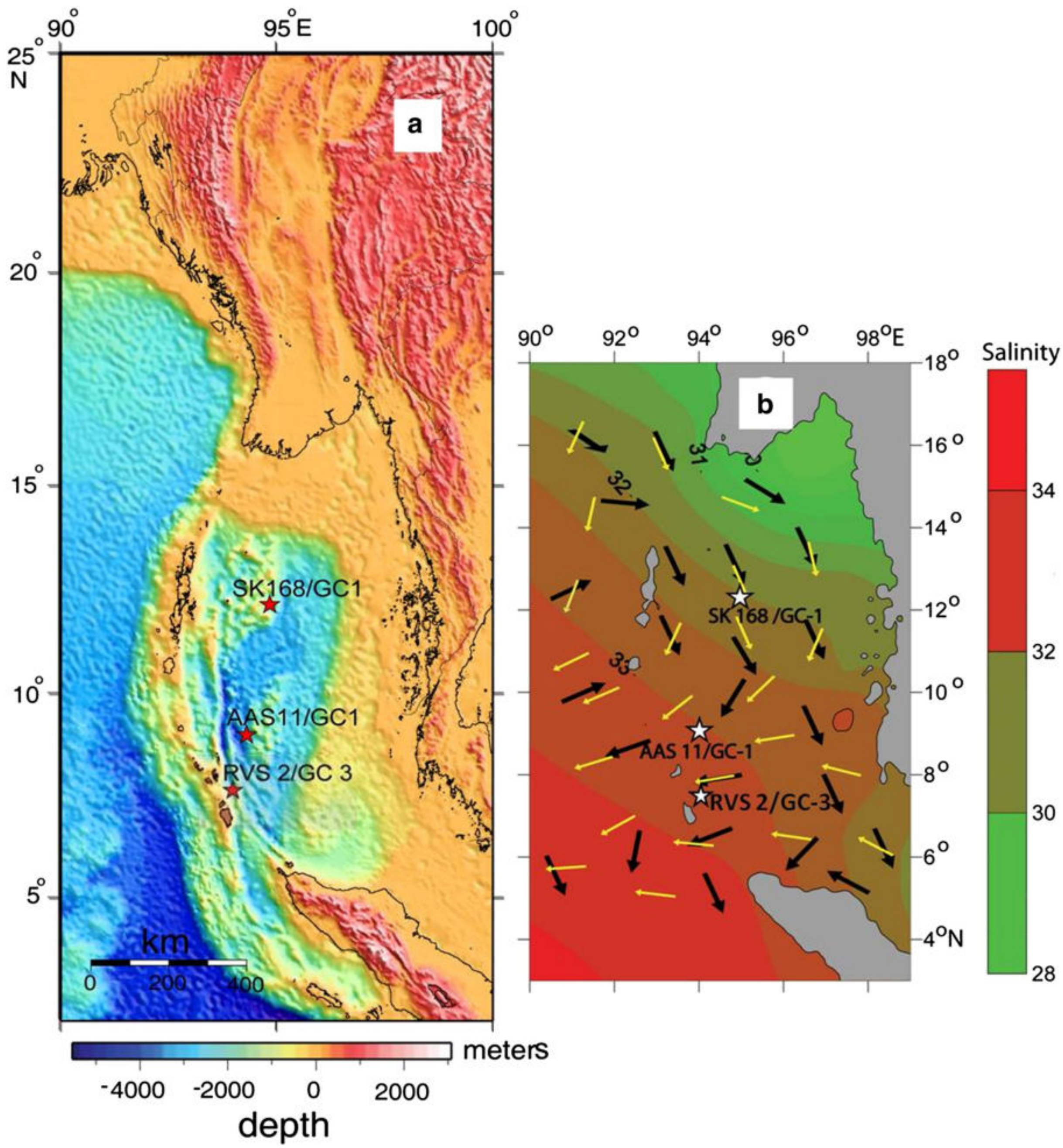

Fig. 1. Map showing core locations in the Andaman Sea in the eastern Indian Ocean: (a) bathymetry of the Andaman Sea along with core locations; (b) salinity (annual salinity at the surface, www.nodc.noaa.gov) and monsoon currents in the Andaman Sea. Black arrow, summer monsoon; yellow arrow, winter monsoon (modified from Brown, 2007 and references therein).

1.1. Planktonic foraminiferal flux in the north-eastern Indian Ocean

Sediment trap experiments from the north-eastern Indian Ocean have demonstrated a large influence of freshwater runoff (seasonal monsoons) on planktonic foraminifera flux (Guptha et al., 1997; Unger et al., 2003 and Stoll et al., 2007). Additionally, there is a significant knowledge base on planktonic foraminiferal distribution based on sediment and plankton tow samples from the BoB (Bé, 1977; Cullen, 1981; Cullen and Prell, 1984; Frerichs, 1968, 1971). Among our profiles, *N. dutertrei* is used as a proxy for freshwater runoff and resultant low salinity (Guptha et al., 1997) and *G. rubescens* is used as a proxy indicator of cold temperatures, showing higher abundances in the north-eastern Indian Ocean (Frerichs, 1971; Cullen, 1981). These studies show that *G. rubescens*, a tropical to subtropical species, has a wide distribution in the surface sediments of the Indian Ocean. It is a very abundant species in the Andaman Sea and contributes nearly 17% to the plankton population (Frerichs, 1971). Frerichs (1968) first noticed the importance of *G. rubescens* in the north-eastern Indian Ocean and documented its usefulness in demarcating the glacial sub-stages (an indicator of cold climatic intervals) in the last glacial period as well as a stratigraphic marker for demarcating the Pleistocene–Holocene boundary. High abundances of *G. rubescens* are found during cold glacial periods whereas low abundances are found during warm interstadials.

N. dutertrei is a tropical to temperate species and lives mainly within the thermocline, near the chlorophyll maximum (Fairbanks et al., 1982; Kawahata et al., 2002). It is also abundant in warm water and low salinity areas with high productivity (Bé, 1977; Prell and Curry, 1981; Thompson, 1981; Pflaumann and Jian, 1999). Its high abundances in the northern BoB is interpreted as a result of freshwater dilution (Guptha et al., 1997). Cullen (1981) was the first to report the high abundance of *N. dutertrei* during very low surface salinity in the BoB resultant of increased freshwater flux. The trap studies from the BoB shows that highest flux of *N. dutertrei* during July to August when salinity is low due to excess freshwater influx (Fig. 2). In the three sediment traps, highest abundance of *N. dutertrei* is seen in the northern part of the BoB (NBBTN, 17°27′N) where salinity is very low during July and August due to very high freshwater dilution (Fig. 2). Shell flux of *N. dutertrei* systematically decreases towards the south (NBBT and CBBT) and indicates clear control of freshwater influx and resultant salinity dilution on its distribution. But these proxy profiles have not been applied in the north-eastern Indian Ocean. In view of the absence of sediment trap/plankton settling flux data from the Andaman Sea, it is assumed that the planktonic foraminiferal distribution and flux in the Andaman Sea is similar to that of the BoB proper as both regions are under the influence of immense freshwater runoff.

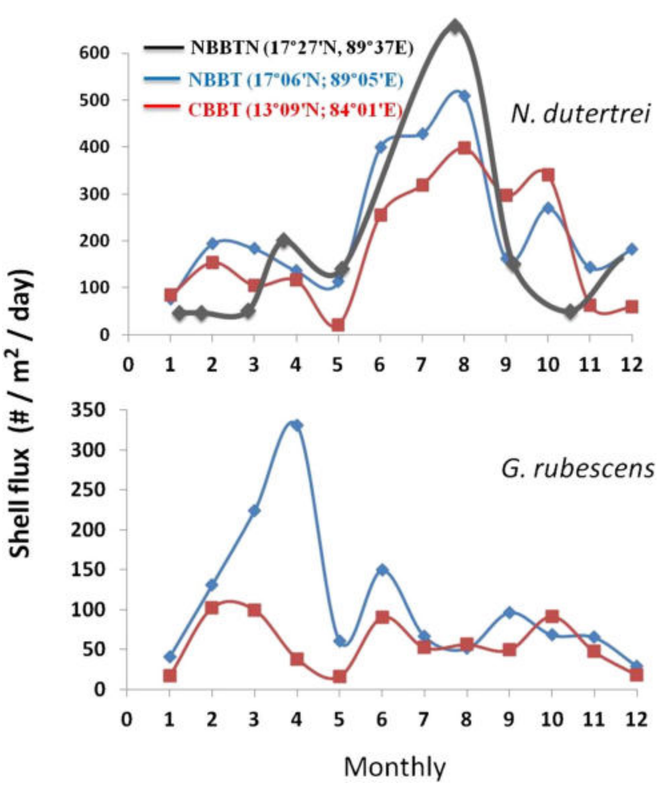

Fig. 2. Monthly flux of the planktonic foraminiferal species viz. *N. dutertrei* and *G. rubescens* in the BoB for the different trap locations (data from Guptha et al., 1997; Stoll et al., 2007).

1.2. Salinity, temperature and monsoon circulation in the Andaman Sea

The Andaman Sea is a marginal sea located in the eastern part of the north-eastern Indian Ocean (Fig. 1a). As in the case of the northern BoB, the Andaman Sea receives large amounts of fresh water annually from the Irrawaddy catchment with most of the outflow occurring during the summer to late fall (Rashid et al., 2007). The Irrawaddy River drains ~428 km^3 of fresh water annually to the Andaman Sea (Milliman and Meade, 1983). As a result of a freshwater influx, salinity reduces to a minimum value during summer monsoon (July to August; Varkey et al., 1996). The annual average salinity at our northern core location (SK 168) is nearly 31.5‰ (Fig. 1b). As a result, a larger salinity gradient exists between the peak and inter monsoon periods. The annual surface water temperature ranges from 28 °C to 30 °C and is well mixed to a depth of 50 m leading to stratification which hinders vertical mixing (Sarma and Narvekar, 2001).

The Andaman Sea experiences a seasonal reversal in surface circulation similar to that of the Arabian Sea (Fig. 1b). The maximum water depth in the Andaman Sea is 4400 m and it is inter-connected with the BoB via several openings viz., the Deep Prepares Channel, Ten Degree Channel and the Great Channel (Fig. 1a). The presence of shallow sills (maximum depth is about 1300 m) has significant impacts on intermediate to deep water circulation in the Andaman Sea. Antarctic Intermediate Water (AAIW) enters the Andaman Sea through the shallow sills as a mixture of overlying water mass containing Subantarctic Mode (SAMW), AAIW, high salinity outflows from the Persian Gulf and the Red Sea (Naqvi et al., 1994; Sarma and Narvekar, 2001).

2. Materials and methods

Sediment cores SK 168, AAS 11 and RVS2 were collected along a north–south transect in the Andaman Sea (Fig. 1a). Core SK 168 (11°42.463′N; 94°29.606′E, water depth: 2064 m) was collected during the 168th cruise of ORV Sagar Kanya from the Alcock Seamount Complex in the Andaman Sea. Sampling protocols and procedures were reported in Sijinkumar et al. (2010). A total of 123 samples were selected for the present analysis. Core AAS11 (9°00′N; 94°17′E, water depth: 2909 m) was collected during the 11th expedition of RV A.A. Sidorenko and sub-sampled at 1 cm intervals down to 20 cm; alternatively, 1–2 cm intervals for the rest of the core. RVS 2/GC 3 (07°42.501′N; 93°58.001′E, water depth: 2301 m) was collected during the Indian expedition onboard the German Research vessel F.S. Sonne. The locations of the cores are ideal for investigating both the spatial and temporal variability of the Irrawaddy runoff and monsoon climate.

For foraminiferal analysis, about 10 g of dried samples were soaked in Milli-Q water overnight and washed through a 63 μm mesh sieve. Later, the dried filtrate was sieved through 125 μm mesh sieve. The coarse fraction (>125 μm) was split into several aliquots to reduce the total number of planktonic foraminifera to a minimum of 300 individuals for quantitative and qualitative analysis of planktonic foraminifera assemblages under a stereo zoom binocular microscope. The abundance of *G. rubescens* and *N. dutertrei* relative to total planktonic foraminifera were calculated. Their abundances in one gram of sediment were counted, which helped in calculating the mass accumulation rate (MAR). The benthic foraminiferal diversity is very low, hence only the total number of benthic foraminifera were counted. The taxonomic identification to species level followed that of Kennett and Srinivasan (1983). Age models using Accelerator Mass Spectrometer (AMS) ^{14}C dates of planktonic foraminiferal tests for all the three cores were published before (Sijinkumar et al., 2010; Sijinkumar et al., 2015).

3. Results

In order to assess changes in foraminiferal abundances, we have calculated relative abundance, absolute abundance and MAR of *G. rubescens* and *N. dutertrei* (Fig. 3). The temporal changes in the abundances of *G. rubescens* and *N. dutertrei* are compared and plotted along with oxygen isotope record of core SK 168 (Fig. 3a). The relative, absolute and MAR of *G. rubescens* show similar temporal variations (Fig. 3). The correlation between organic carbon content with benthic foraminiferal abundances of all cores are shown in Fig. 4. Our planktonic, benthic foraminiferal and pteropod records are plotted along with the oxygen isotopes of the Greenland ice core record (Blunier and Brook, 2001) in Fig. 5. *G. rubescens* shows very large variations for the last 54 cal ka BP (Figs. 3, 5). The abundance of *G. rubescens* varies between 1% and 13% with an average value of 5%, and is very high during the Heinrich events, LGM, YD and mid-Holocene. Low abundances were recorded during D/O events (1–14) (Figs. 3, 5). An abrupt reduction of *G. rubescens* abundance is seen during the last glacial to Holocene transition and the abundances were low throughout the Holocene (Fig. 3).

Similar to *G. rubescens*, the relative, absolute and MAR of *N. dutertrei* show similar temporal variations (Fig. 3). *N. dutertrei* shows high relative abundance between 36 and 34 ka, 25–22 ka, the B/A, the early Holocene, 6–5 ka and lower abundance during early MIS 3, Heinrich events, the deglacial, YD and the mid-Holocene. A gradual decrease in its abundance from 25 ka to 15 ka is followed by a gradual increase from 15 ka to 8 ka (Fig. 5). A characteristic inverse relationship is seen between *N. dutertrei* and *G. rubescens* abundance (Fig. 5). A large and significant oscillation in benthic foraminiferal abundances is seen from H1 and throughout the Holocene (Fig. 4). Very high abundances of benthic foraminifera are seen during early MIS 3 (49–46 and 43–40 cal ka BP) and a considerable increase in abundance is also seen during early Holocene. Low abundances are seen during H3, H2, the deglacial, H1, the YD and the mid-Holocene (6–4 cal ka BP). The high organic carbon content during 43–40 cal ka BP and B/A coincide with higher abundance of benthic foraminifera (Fig. 4). The high abundance of total benthic foraminifera during early MIS 3 is not reflected in the *N. dutertrei* abundances (Fig. 5).

4. Discussion

4.1. Planktonic foraminifera abundances and dissolution

Planktonic foraminifera are very sensitive to environmental variations making them ideal proxies for changing climate and oceanic conditions. Their abundance variations in ocean sediments reflect changes in productivity, preservation potential and terrigenous supply. The abundance variation of planktonic foraminifera may also be influenced by selective dissolution of susceptible species. We rule out that the high and low abundances of *N. dutertrei* and *G. rubescens* are related to dissolution by comparison with dissolution-resistant species. The total relative abundance of dissolution resistant species (usually with thick walled shells, less prone to dissolution) are less than 30%, which suggest

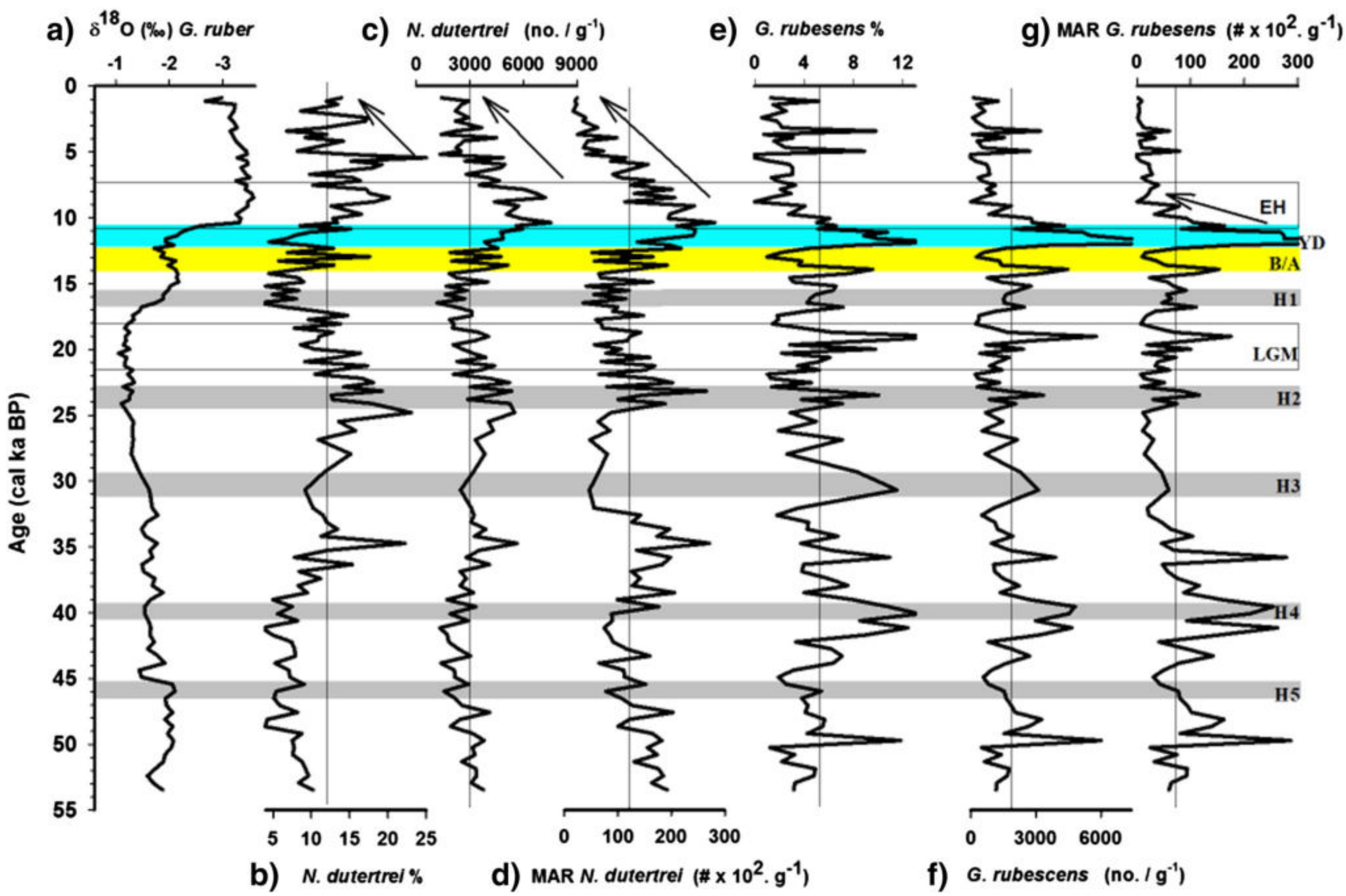

Fig. 3. Relative, absolute and mass accumulation rates (MAR) of planktonic foraminifera of core SK 168: (a) $\delta^{18}O$ *G. ruber*; (b) relative abundance of *N. dutertrei* (%); (c) absolute abundance of *N. dutertrei* (no. g^{-1}); (d) MAR of *N. dutertrei*; (e) relative abundance of *G. rubescens* (%); (c) absolute abundance of *G. rubescens* (no. g^{-1}); (d) MAR of *G. rubescens*.

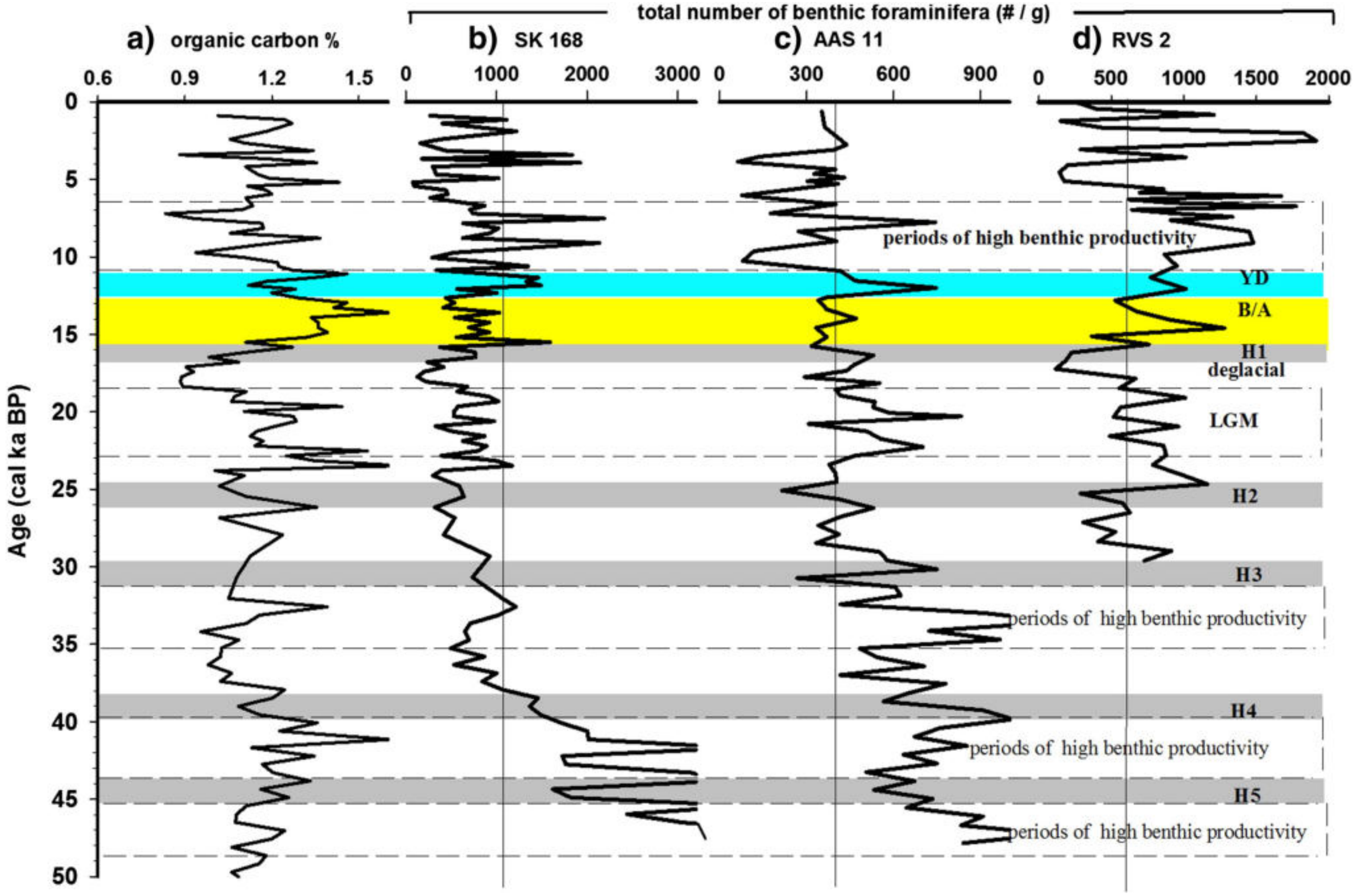

Fig. 4. Downcore variations of benthic foraminiferal abundances from the Andaman Sea: (a) organic carbon content (%) (SK 168, Sijinkumar et al., 2010); (b) total benthic foraminifera in core SK 168; (c) core AAS 11 and (d) in core RVS 2 (vertical solid line indicates average value).

good preservation of planktonic foraminifera (Cullen and Prell, 1984). Further, the carbonate lysocline of this part of the Indian Ocean is estimated to be 4200 m (Kolla et al., 1976) whereas our cores are located well above the lysocline. Good carbonate preservation in the Andaman Sea may be due to the warm deep water relative to that of BoB with an approximate offset of 2 °C (Sarma and Narvekar, 2001). The high temperature of the deeper water in the Andaman Sea lowers the carbonate saturation depth in the region and favours better preservation (Sijinkumar et al., 2010). Hence, *N. dutertrei*, *G. rubescens* and total benthic foraminifera proxy profiles for the last 54 cal ka BP dominantly reflect changes in salinity due to freshwater influx, SST and productivity respectively and display large millennial-scale oscillations in the freshwater influx driven by summer monsoonal fluctuations.

4.2. Andaman Sea foraminiferal response to North Atlantic climate change

A comparison of the GISP2 ice core isotope and the Andaman Sea records shows that rapid temperature variations documented in the ice core (D/O and Heinrich events) during the last glacial period were also present in the foraminiferal temperature record (Figs. 4, 5). During the last glacial period, thirteen D/O-like events with minima in *G. rubescens* are recorded in the Andaman Sea (Fig. 5). Although not as highly resolved as the ice core data, the minima and maxima of *G. rubescens* abundance during the last glacial corresponds to warm interstadials (D/O events) and cold stadials (Heinrich events H5-H1, LGM and YD), respectively. The abrupt changes in the abundance of *G. rubescens* closely matches those in the ice core record, illustrating a link to high latitude North Atlantic variability, consistent with previous interpretations from the northern BoB and Andaman Sea (Colin et al., 1998; Kudrass et al., 2001; Marzin et al., 2013). During D/O events, *G. rubescens* fall as low as 1% whereas abundances of *N. dutertrei*, a freshwater/low saline species increased. The high abundances of *N. dutertrei* during D/O events suggest greater freshwater influx (Irrawaddy runoff and direct precipitation).

Corresponding to maxima in *N. dutertrei* abundance, especially during the Early Holocene, the total benthic foraminifera abundances were also high, suggesting increased export flux of carbon to the sea floor. This is also indicated in the increased organic carbon content (Fig. 3). However, low abundances of benthic foraminifera are seen during B/A when *N. dutertrei* were high. These results suggest that during periods of high productivity in the early Holocene, the surface changes in the hydrography were also reflected in benthic biomass as deep-sea benthic foraminifera are sensitive to the total export flux of organic carbon to the seafloor (Loubere and Fariduddin, 1999). Rashid et al. (2007) also reported increased Irrawaddy River outflow and lowered salinity during B/A and the early Holocene on the basis of the oxygen isotope record. Benthic foraminiferal assemblages from Santa Barbara Basin have also been shown to exhibit major faunal and ecological switches associated with D/O events (Cannariato et al., 1999).

N. dutertrei, proxy for freshwater dilution shows large variations for the last 55 cal ka BP which are interpreted as fluctuations of Indian monsoon. The lower abundance of *N. dutertrei* during Heinrich events, the deglacial, the YD and mid- to late-Holocene suggests reduced influx of fresh water (Irrawaddy River and direct precipitation). The high abundances of *G. rubescens* and low abundances of *N. dutertrei* during cold stadials (Heinrich events, YD) reflect the interplay of the monsoon and North Atlantic climate changes during last glacial cycle. Our faunal evidence strengthens earlier magnetic and isotope-based reconstructions of weak summer monsoon during stadials in the Andaman Sea (Colin et al., 1998; Rashid et al., 2007).

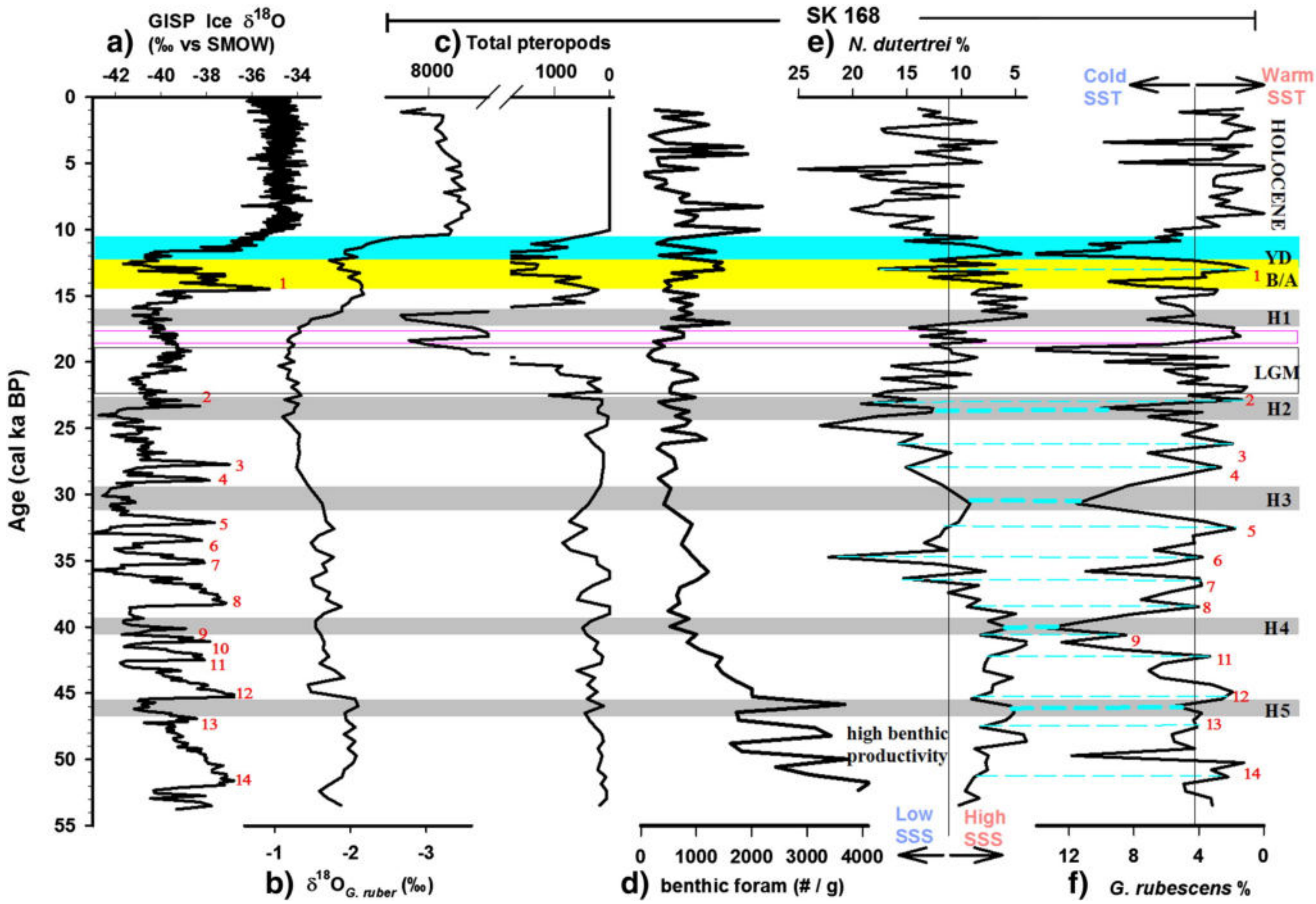

Fig. 5. Correlation of the North Atlantic climate events with Andaman Sea record of core SK 168: (a) Greenland ice core record (GISP2 ice ^{18}O) (Blunier and Brook, 2001); (b) δ^{18}O of *G. ruber*; (c) total pteropods (Sijinkumar et al., 2010); (d) total benthic foraminifera; (e) *N. dutertrei* %; (f) *G. rubescens* %. D/O events are marked as 1–14. Dotted lines denote the inverse relationship between *N. dutertrei* and *G. rubescens* during D/O and Heinrich events.

Colin et al. (1998) also show that Heinrich events are characterized by lower values of the chemical index of alteration implying a lower degree of chemical weathering related to significantly drier conditions on the land. Reduced freshwater runoff was also reported from Chinese loess record which were interpreted as lower continental weathering intensity (Guo et al., 1996). Good preservation of pteropods can also be seen during cold stadials such as YD and Heinrich events which was interpreted as weakened summer monsoon (Sijinkumar et al., 2010). Sudden reduction in the abundance of the *Pulleniatina obliquiloculata* (*Pulleniatina* minimum event) during cold stadial period YD is also reported from the Andaman Sea (Sijinkumar et al., 2011). These faunal responses, taken together with the other lines of independent evidences strongly support a direct link to variation of summer monsoon which, in turn seem to strongly correlate with North Atlantic climatic events.

With the limitation of AMS ^{14}C chronology for beyond 25 ka and poor sampling resolution for DO events, our records substantiate the earlier notion that the rapid cold events of the North Atlantic (Heinrich events) during the last glacial stages are characterized by a weaker summer monsoon rainfall over the Himalaya via an atmospheric teleconnection (Colin et al., 1998). Further, our *G. rubescens* record also shows that during the last glacial the strong SST variability are synchronous with the D/O events and the weak monsoon was associated with the cooling events (Heinrich events) in the North Atlantic (Sirocko et al., 1996; Schulz et al., 1998). The high-resolution records (50–100 year/sample) of *G. rubescens* and *N. dutertrei* during the last glacial period will better resolve the North Atlantic rapid climate change and its atmospheric teleconnection to Indian Ocean summer monsoon variability.

The sudden change in total pteropods, very low organic carbon and low to moderate abundances of total benthic foraminifera and *N. dutertrei* is seen during the deglacial is interpreted as the result of weak summer monsoon and productivity in the Andaman Sea. Our record shows that whenever there is a reduction of fresh water, the increased salinity periods are characterized by low benthic foraminiferal abundance and bottom water productivity. During the LGM, moderate to high organic carbon content suggest that productivity is higher than deglacial but lower than that of present may be due to enhanced winter monsoon circulation during LGM (Duplessy, 1982; Sarkar et al., 1990). The good preservation of pteropods during the glacial as well as the high relative abundance of mesopelagic pteropods over epipelagic forms suggests a well ventilated water column with weak OMZ, apparently driven by intense winter monsoon (Sijinkumar et al., 2010). The productivity changes in the Andaman Sea are in contrast to that of the eastern Arabian Sea where upwelling induced high productivity was seen during glacial period compared to the Holocene (Singh et al., 2011). However, poor productivity is seen in the eastern Arabian Sea during the Heinrich events as in the Andaman Sea. The productivity fluctuations in the Andaman Sea are similar to western Arabian Sea, where denitrification was found to be high during the warm phases of the D/O events and low during the cold phases suggesting higher primary productivity (Altabet et al., 2002). The difference in the productivity pattern between the Andaman Sea and the eastern Arabian Sea may be due to the difference in summer and winter monsoon strength in both the seas.

4.3. Holocene climate fluctuations recorded in the Andaman Sea

The Holocene is characterized by major changes in benthic abundance along with *N. dutertrei* and *G. rubescens* suggesting unstable climatic and oceanographic conditions in the Andaman Sea. The study by Bond et al. (2001) also shows that glacial-like climatic fluctuations are present during the Holocene as well, although at reduced amplitude. The highest abundances of *G. rubescens* is seen during last glacial–Holocene transition, then gradually decreases to consistently low abundances during Holocene which may provide an indication for the demarcation of MIS 2–MIS 1 boundary as suggested by the Frerichs (1968). The two sudden spikes of *G. rubescens* seen during the Holocene (5 and 4 cal ka BP) may represent abnormal cooling of Andaman Sea surface waters, and may be correlative with the Holocene ice rafted debris events 3 and 4 (Bond et al., 1997).

The steady increase of *N. dutertrei* during the early Holocene indicates greater influx of Irrawaddy River water as a result of enhanced summer monsoon circulation. There are several continental and marine records indicating strengthened summer monsoons during the early Holocene (Govil et al., 2011; Gupta et al., 2003; Rashid et al., 2007; Schulz et al., 1998; Anand et al., 2008). Our record also shows several short-scale fluctuations in benthic productivity, poor pteropod preservation and negative excursions in oxygen isotope record and large variations in *N. dutertrei* and *G. rubescens* abundance suggesting fluctuations in Irrawaddy runoff. This evidence shows that teleconnections between the Indian Ocean summer monsoon and the North Atlantic climate were prevalent not only during the last glacial but also in the Holocene.

A sudden change in benthic and *N. dutertrei* abundance are seen between 8 and 7 cal ka BP, indicating an interruption of the progressive enhancement of summer monsoon from 11 ka onwards as seen in the *N. dutertrei* abundance. Terrestrial paleo lake records from northwestern India have also shown an abrupt weakening of summer monsoon during 8.2 ka (Dixit et al., 2014). A progressive gradual reduction in the abundance of *N. dutertrei* from mid-to late-Holocene and the enrichment of *G. ruber* $\delta^{18}O$ suggests a gradual trend of decreasing freshwater outflow and direct precipitation driven by deteriorating summer monsoon circulation. Overall, the abundance of *G. rubescens* decreased during warm present interglacial compared to the cold glacial periods (MIS 2, MIS 3) whereas *N. dutertrei* abundance steadily increased from early Holocene in pace with increased summer monsoon.

5. Conclusions

Abrupt changes in the climate and oceanography related to D/O events and Heinrich events of the North Atlantic are documented in the Andaman Sea using the abundance variation of *N. dutertrei*, *G. rubescens* and benthic foraminifera. Our faunal records show large temporal variations indicating substantial changes in the surface to bottom hydrography in the Andaman Sea. *G. rubescens* minima and maxima abundance during the last glacial correspond to D/O events and cold stadials (Heinrich events, LGM and YD) respectively. The D/O events are marked by very low *G. rubescens* and high *N. dutertrei* abundances which indicate freshened surface water reflecting a combination of direct precipitation and strengthened Irrawaddy outflow. The inverse relationships of *G. rubescens* with the low saline species *N. dutertrei* during D/O events further support the view of correlative monsoon changes in the Andaman Sea and rapid climate changes in the North Atlantic. The lower abundance of *N. dutertrei* (corresponds to *G. rubescens* maxima) during Heinrich events, deglacial, YD and mid- to late-Holocene suggests reduced influx of fresh water from the Irrawaddy and direct precipitation as a result of weakening of summer monsoon driven by the teleconnection between North Atlantic climate and Indian monsoon. Overall, the abundance of *G. rubescens* decreased during warm present interglacial compared to the cold glacial periods (MIS 2, MIS 3) whereas *N. dutertrei* abundance steadily increased from early Holocene in pace with increased summer monsoon.

Acknowledgements

We thank the Director, National Institute of Oceanography, Goa, for the permission to publish this paper. Council of Scientific and Industrial Research (CSIR) and the Ministry of Earth Sciences (Government of India), New Delhi are thanked for providing ship time. Captain and crew of ORV Sagar Kanya, F.S. Sonne and A.A. Sidorenko are thanked for their help. Funding for the ongoing work is supported by CSIR Networked Project GEOSINKS. SAV acknowledge UGC for awarding Raman post-doctoral fellowship to Brown University, USA.

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