Intense deep convective mixing in the southeast Arabian Sea linked to strengthening of the northeast Indian monsoon during the middle Pliocene (3.4 Ma)

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The climate of the Indian Ocean is dominated by monsoon reversals, influencing hydrography and biogeochemistry of the Indian Ocean as well as land vegetation through changes in precipitation. During summer or southwest monsoon season, intense upwelling zones driven by Ekman spiral appear in the western and eastern parts of the Arabian Sea that enhance surface primary production and thus proliferation of distinct fauna and flora. During the winter season, northeast monsoon winds cause deep convective overturning (mixing) that injects nutrients to the surface ocean and increases surface production. As a result, the primary production in the Arabian Sea has bimodal annual distribution. The present study analyses 5.6 Ma record of surface-dwelling planktic foraminifera, *Globigerina bulloides*, *Globigerinoides ruber* and *Globigerinoides sacculifer* from Deep Sea Drilling Project Site 219, southeast Arabian Sea to understand changes in the surface ocean as driven by the Indian monsoon coinciding with the northern hemisphere glaciation (NHG). An increase in mixed-layer species at ~3.4 Ma suggests intense deep convective overturning caused by strong NE monsoon winds related to strengthening of NHG. *G. bulloides* shows a high positive relation with *G. ruber* during the past 3.4 Ma and a weak relation in the early Pliocene (5.6–3.4 Ma). The high *G. bulloides* percentages during the past 3.4 Ma could be linked to the injection of nutrients in the top layer by the advecting sub-surface nutrient-rich water.

Keywords: Deep convective mixing, NE monsoon, southeast Arabian Sea.

THE Pliocene is marked by a transition from a ‘greenhouse world’[1] during 5–3.2 Ma to a world marked by periodical waxing and waning of ice sheets (since 3.2–2.4 Ma), when the northern hemisphere witnessed major ice volume expansion[2]. During the early Pliocene warmth, the tropics were in a permanent El Niño state with weak Walker circulation and deep thermocline[3]. The global climates underwent major reorganization during the middle Pliocene (3.2–2.4 Ma), marked by major expansion of the northern hemisphere glaciation (NHG), leading to more abrupt changes in climate and ocean circulation[2–4]. Intensification of NHG may have significantly cooled deep waters (formed at high latitudes) that subsequently increased deep ocean stratification[3,5]. Increased ocean stratification caused ventilated thermocline to shoal, allowing cold water to upwell in the tropics and subtropics, thereby enhancing global cooling[3].

Intensification of NHG drove significant changes in land vegetation, triggered African aridification and increased Indian monsoon seasonality with more intense winter or northeast monsoon[6–11]. During cold intervals the wind intensity (including NE monsoon) increases, which leads to intense convective mixing (overturning) at high and low latitudes. Intense NE monsoon winds driven by NHG could have brought significant changes in surface oceanography, and fauna and flora of the northern Indian Ocean. To understand the impact of the changing monsoonal seasonality, in response to NHG intensification, on surface ocean in the southeast Arabian Sea, this study analysed 5.6 million-yr-old proxy record of surface-dwelling planktic foraminifera, *Globigerina bulloides*, *Globigerinoides ruber* and *Globigerinoides sacculifer* from Deep Sea Drilling Project (DSDP) Site 219. We selected these planktic foraminifera because of their dominance at Site 219 and their preference to distinct water masses.

Site 219 was drilled during DSDP Leg 23 on the crest of the Laccadive-Chagos Ridge, off the southwest coast of India, SE Arabian Sea (9°01.75′N, 72°52.67′E; water depth 1764 m; Figure 1). At present, this site lies within an area where surface primary production is higher due to summer or southwest monsoon-induced upwelling and is thus good for the study of monsoon-driven changes in the surface ocean (Figure 2). However, during NE monsoon season, surface production decreases significantly.

We analysed 111 core samples of 10 cm^3 volume from a 68 m long sediment sequence from Site 219 spanning the last 5.6 Myr. Samples were soaked in water with half a spoon of baking soda for 8–12 h, and washed over a 63 μm size sieve. The washed samples were dried in an electric oven at ~50°C and transferred into labelled glass vials. Hard sediment samples were soaked in water with 2–3 drops of 2% hydrogen peroxide. We generated census data of planktic foraminifera *G. bulloides*, *G. ruber* and *G. sacculifer* from an aliquot of ~300 specimens from >150 μm size fraction. The per cent distribution of each species is shown in Figure 3. The >150 μm size fraction allows us to compare our results with those from the other ocean basins.

Linear correlation between *G. bulloides* and *G. ruber* was carried out to understand the response of the upper ocean in the SE Arabian Sea to changes in monsoonal wind intensities over the past 5.6 Ma (Figure 4). The correlation was carried out for the whole 5.6 Ma interval (Figure 4 *a*), as well as 5.6–3.4 Ma and 3.4–0 Ma intervals (Figure 4 *b* and *c*) with value of correlation coefficient (*R*) calculated in each case. The sampling interval is

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at low resolution during 5.6–3.4 Ma than during 3.4–0 Ma owing to a change in sediment accumulation rate. We could not do much since samples were procured at near equal interval for a different study and were pre-washed.

We applied the age model for Site 219 based on planktic foraminiferal datums suggested in Gupta and Thomas[12]. The sediment accumulation rate at Site 219 was high from 5.6–3.4 Ma and moderate from ~3.4–2.4 Ma, with a major increase[12] since ~2.4 Ma. The interpolated numerical ages are updated to the Berggren *et al.*[13] timescale, with an average time resolution of ~50 Kyr per sample.

G. bulloides d'Orbigny is a near-surface give water depth and its solution susceptibility-dwelling planktic foraminifer, conventionally known from the transitional and sub-polar water masses[14], but has also been found in significant proportions in tropical and subtropical wind-driven upwelling regions of the northern Indian Ocean[15]. This species produces high shell fluxes in monsoon-driven high-productivity regions of the tropical NW Indian Ocean, including the Arabian Sea, and has widely been used in determining SW monsoon wind intensities during the late Quaternary and the Holocene[15–18]. Sediment trap studies off Somalia indicate highest shell fluxes of *G. bulloides* (21–54%) during summer (SW) monsoon season owing to intense upwelling of cold and nutrient-rich waters[19,20]. Curry *et al.*[21] also observed maximum shell fluxes of *G. bulloides* below SW monsoon-induced upwelling zones in the Arabian Sea. During the non-upwelling or intermonsoon periods, however, *G. bulloides* only makes up to 5–12% of the assemblage[20].

G. ruber is a spinose planktic foraminifer living in the photic zone (top 50 m) of the water column in the tropical and subtropical areas with a sea surface temperature (SST) of 14–30°C (optimum 21–28°C), and optimum sea surface salinity (SSS) of 34.5–36.0 psu (ref. 22). It is a symbiont-bearing species (with zooxanthellae), preferring oligotrophic regions with a deep mixed layer[23] and is susceptible to dissolution[14,24]. *G. ruber* most commonly occupies the warm mixed layer above the thermocline[25] and shows maximum abundance in the top 20m of the mixed layer in the early autumn when thermocline begins to break down[26]. In the Arabian Sea, *G. ruber* proliferates in relatively warm and oligotrophic surface waters during both the upwelling and non-upwelling (both monsoon) seasons owing to its preference to a higher optimum temperature, and the fact that this species may obtain nutrition from its symbionts[20]. Non-upwelling species produce high or maximum fluxes during the SW monsoon and continue to persist during the non-upwelling periods[20].

G. sacculifer is also a shallow-dwelling (surface depth habitat top 30–50 m) mixed layer, tropical to subtropical species, tolerating a SST range of ~17–30°C (optimum 27–30°C), SSS optimum of ~34.9 psu and phosphate content of ~0.5 μg l^{-1} (ref. 22). This species prefers to live in warm-water, low-salinity, mixed-layer oligotrophic settings[27,28]. The species is susceptible to dissolution and prefers low seasonal changes in SST and vertical temperature gradients, and is not well suited to large seasonal salinity changes[14]. Duplessy *et al.*[29] have suggested that *G. sacculifer* secretes its last chamber below the thermocline. *G. ruber* (white) and *G. sacculifer* mirror regions of highest surface water temperatures and low primary production in the central and southern Arabian Sea[30]. Oberhänsli *et al.*[31] observed increased percentages of *G. sacculifer* with increasing oxygen content and slightly lowered salinity in the South Atlantic. It has been observed that when the depth of thermocline is shallow mixed-layer species like *G. sacculifer* decreases[28].

G. bulloides and *G. ruber* show a weak positive correlation ($R = 2.2$) from 5.6 to 3.4 Ma, following which the two species show good parallelism ($R = 0.57$; Figure 3). *G. sacculifer*, on the other hand, shows increased percentages from 3.4 to 2.2 Ma, when *G. bulloides* shows a decrease. The value of R between per cent *G. bulloides* and *G. ruber* is 0.48 for the whole 5.6 Ma period (Figure 4). The good correlation between *G. bulloides* and *G. ruber* since 3.4 Ma suggests that the character of the upper ocean in the SE Arabian Sea changed due to a switch in the monsoon wind intensity following strengthening of the NHG.

In the Arabian Sea, where summer monsoon induces upwelling, surface primary production is generally higher during interglacial times[16,32,33]. On the other hand, Rostek *et al.*[34] observed higher NE monsoon-driven palaeoproductivity in the eastern Arabian Sea caused by deeper mixing during glacial times. Today, NE monsoon winds cause deep convective overturning (mixing) in the Arabian Sea, thereby injecting nutrient-rich subsurface waters into the euphotic zone[34–37], which results in a moderate increase of surface temperature. Veldhuis *et al.*[38] suggested that wind-induced mixing results in entrainment of nutrient-rich deeper water to the surface, resulting in increased production of phytoplankton and biomass. During the 1995 US Joint Global Ocean Flux Study, Hansell and Peltzer[39] observed highest total organic carbon concentrations in the mixed layer during the NE monsoon period, which serves as a source of nutrients to the euphotic zone. Elevated levels of surface chlorophyll and primary productivity are thus associated with deep convective mixing and entrainment during the two monsoon seasons[40].

Population trend of surface-dwelling planktic foraminifera at Site 219 suggests a major shift in the physical character of the surface ocean in the SE Arabian Sea at ~3.4 Ma, indicating a change in monsoon wind intensities. *G. bulloides* and *G. ruber* show almost no correlation during 5.6–3.4 Ma, with moderate *G. bulloides* and decreased *G. ruber* percentages, indicating increased surface stratification. The two species show good parallelism since ~3.4 Ma, indicating an intense deep convective overturning and entrainment of nutrients in the surface ocean due to stronger NE monsoon winds driven by intense NHG. At present very cold winters produce deep convection in the northern North Atlantic, and in general, the colder the winter, the greater is the overturning.

The fact that *G. ruber* proliferates in both the monsoon seasons whereas *G. bulloides* blooms during summer upwelling (high nutrient level), it is likely that the parallelism between the two species was driven by the availability of nutrients due to deep convective overturning, and not upwelling, during strong NE monsoon season. In a typical upwelling setting, *G. bulloides* population increases to more than 20% and can reach up to ~50% of the total population[17]. This suggests that *G. bulloides* population can also increase during intense winter monsoon that entrains chlorophyll-rich subsurface water to the surface, as it does in the present-day ocean. An increase in *G. sacculifer* during 3.4–2.2 Ma perhaps indicates low surface salinities due to increased NE monsoon precipitation.

During the middle Pliocene, the monsoon entered a regime marked by major increase in NHG superimposed by variations in the earth's orbital parameters[11]. A change in monsoon seasonality towards intense winter monsoon is observed during 3–2.5 Ma in the eastern Indian Ocean, coinciding with major expansion of the NHG[11]. It has been observed that during cold intervals the summer monsoon weakens and winter monsoon winds become stronger[6,10,11]. The monsoon underwent more rapid changes during 3.6–2.6 Ma (ref. 10). Thus there is considerable evidence of linkage between NHG and the development of, as well as fluctuations in, the monsoonal system. Gupta and Thomas[11] demonstrated that such weakening of the summer monsoon and initiation of a strong winter monsoon has profoundly affected biota in the eastern equatorial Indian Ocean.

We suggest that monsoon regimes over Site 219 switched between SW and NE monsoons on glacial–interglacial timescale with more influence of the SW monsoon during warm intervals and of the NE monsoon during cold intervals. Since ~3.4 Ma, surface productivity over Site 219 was driven by NE monsoon winds. This study strengthens earlier observations that in the Indian Ocean, monsoon wind regimes changed on glacial–interglacial timescale[32]. This study also suggests that *G. bulloides*, being an opportunist, responds to the input of cold, nutrient-rich waters, irrespective of the mechanism that brings nutrients to the surface. Although in areas of deep convective overturning the *G. bulloides* population is not as high as in upwelling areas, its population certainly shows a positive correlation with the intensity of the convective overturning.

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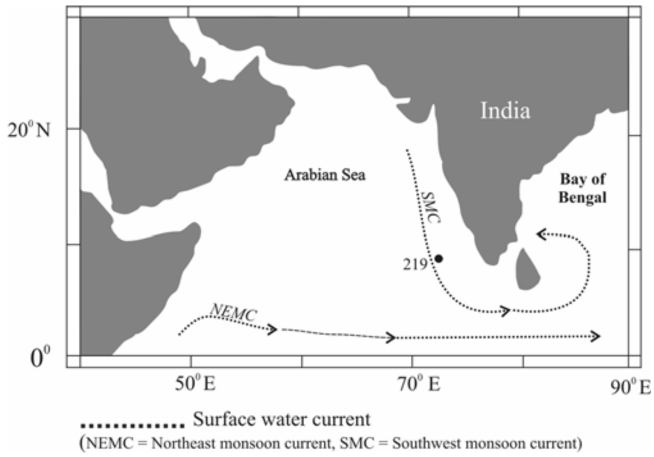

Figure 1. Location map of DSDP Site 219 in the tropical Indian Ocean. The surface ocean currents are from Schott *et al.*[41].

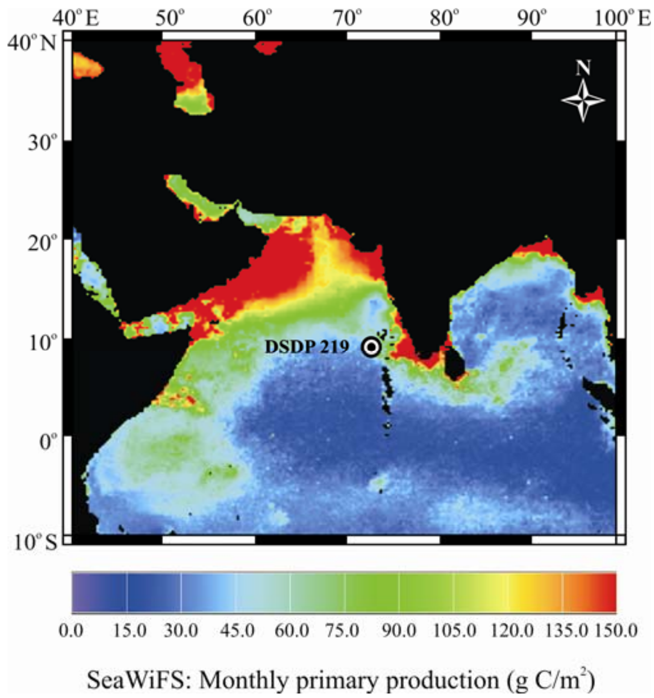

Figure 2. Location of DSDP Site 219 superimposed on the annual primary production map of the Indian Ocean based on SeaWiFS chlorophyll data (averaged over June 1998–August 1998, from http://marine.rutgers.edu/opp/swf/Production/results/all2_swf.html). At present Site 219 lies close to summer monsoon-driven upwelling zone.

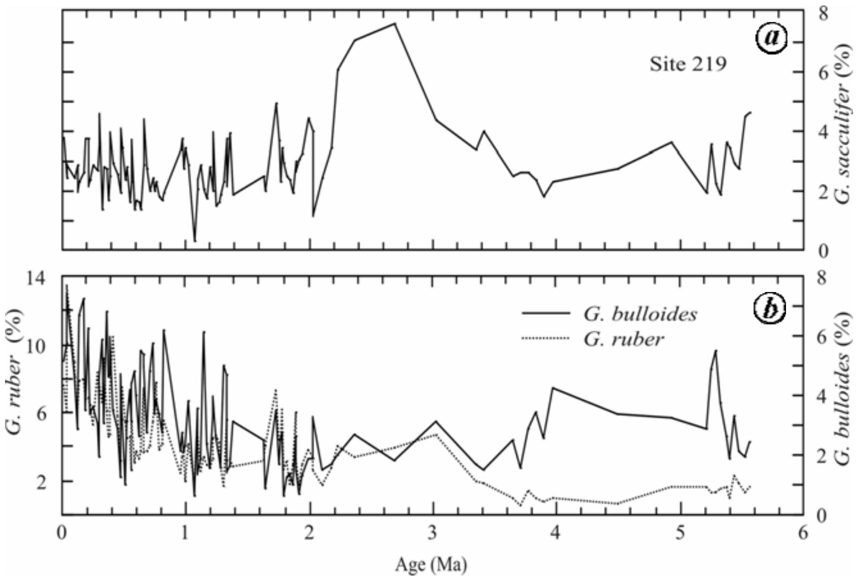

Figure 3. Per cent distribution of planktic foraminifera, *Globigerina bulloides*, *Globigerinoides ruber* and *Globigerinoides sacculifer* during the past 5.6 Ma. *G. bulloides* and *G. ruber* populations deviate out in the early Pliocene (5.6–3.4 Ma) and thereafter show good parallelism contemporaneous with the northern hemisphere glaciation. *G. sacculifer* shows a hump-shaped increase in its population during 3.4–2.2 Ma.

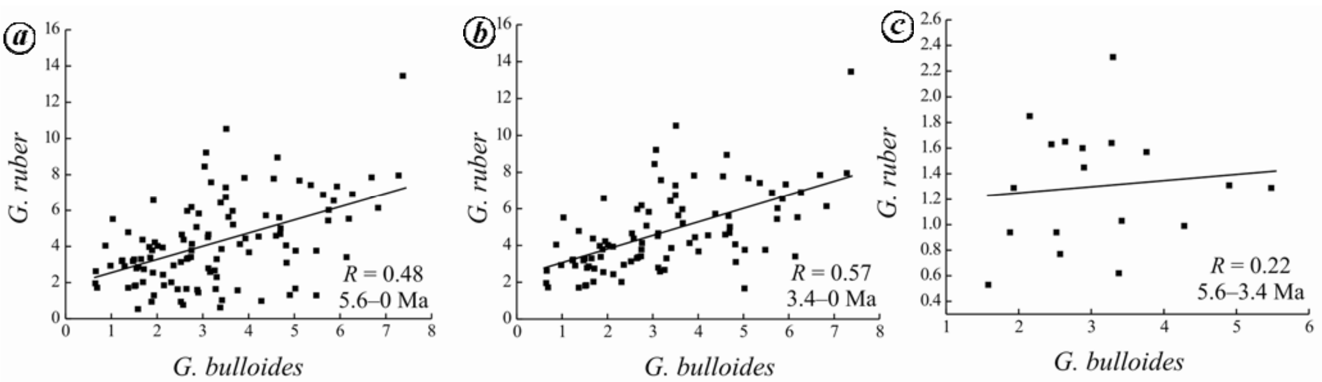

Figure 4. Linear correlation between *G. bulloides* and *G. ruber* over the past 5.6 Ma. The value of correlation coefficient (*R*) is 0.48 for the whole 5.6 Ma period (***a***), 0.57 for the interval 3.4 to the Recent (***b***) and 0.22 for 5.6–3.4 Ma interval (***c***).