Surface circulation in the eastern Indian Ocean during last 5 million years: Planktic foraminiferal evidences

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The paper describes the major circulation changes in the eastern Indian Ocean during last 5 million years based on variation in planktic foraminiferal assemblages in various ODP and DSDP cores examined by various workers. The Late Miocene/Pliocene transition is characterized by weakening of the Leeuwin Current and migration of the polar front towards north. The early Pliocene is marked by closing of the Indonesian Seaway for surface waters and strengthening of the Leeuwin Current, a general warming of the surface waters and thickening of the mixed layer in the eastern Indian Ocean. The Late Pliocene and Pleistocene witnessed severe climatic fluctuations and episodic weakening and strengthening of the Leeuwin Current in response to either ENSO induced changes in the Western Pacific Warm Pool or lowering of sea level and reduction in Indonesian throughflow due to ice sheet expansion.

[Key words: Planktic foraminifera, ocean circulation, Pliocene; Pleistocene, Indian Ocean, foraminiferal evidence, circulation, West Australian current, Indonesian seaway, Leeuwin current]

Introduction

The circulation of the upper layer of the oceans plays a crucial role in controlling world’s climate. Due to high thermal capacity, oceans have become great reservoirs of heat, and large scale transport of ocean waters across the latitudes and longitudes is responsible for making many regions of the world inhabitable. For example the Gulf Stream in the Atlantic keeps Northwest Europe warmer than expected (8°C higher). The volume of waters transported by these ocean currents is very large when compared with the combined discharge of all the rivers of the world e.g. Gulf Stream, transports $113 \pm 8$ Sv water\(^1\) which is 100 times than the combined discharge of all the rivers of the world ($1.18 \pm 0.02$ Sv)\(^2\). The surface currents play a crucial role in modifying climate of the respective regions. In the climate modeling, the ocean circulation finds an important place and study of past behavior of various current systems is a key element in deriving futuristic models for climatic prediction.

Has surface circulation changed in the past?

Surface circulation has been changing in the past because the circulation is caused and affected by the factors which have been changing through the geological time. Major changes in the intensity of oceanic conveyor belt have been demonstrated by a number of workers. Studies have shown temporal changes in the strength of Leeuwin current\(^3,4\), Indonesian throughflow\(^5,8\); Gulf Stream\(^9\); Benguela current\(^10\), Tasman front\(^11\); Kuroshio current\(^12\) and Agulhas current\(^13\) etc. Closing and opening of ocean gateways have also resulted in the changing circulation pattern and climate\(^6,8,14\). Though varying surface circulation pattern due to changing ocean continent geometry is a very slow process taking millions of years, yet it had profound effect on the global climate, e.g. development of Circum Antarctic circulation resulting from northward movement of India, Australia and opening of the Drake Passage\(^15\).

Approaches to study past surface circulation

Because planktic foraminifers are floaters, their distribution in the ocean is largely controlled by prevailing surface circulation. After death, their tests are showered on the ocean floor and to a great extent...
their distribution on the ocean floor reflects the circulation patterns of the surface layers. Planktic foraminifera are also latitudinally provincialised. Thus their biogeography also reflects latitudinal belts. Their paleobiogeographic pattern indicates the changing thermal structure of the oceans. Besides they are also depth stratified. Distinct assemblages characterizing various depths have been identified e.g. Mixed layer assemblage, thermocline assemblage or deep water assemblages. Many planktic foraminifers are nutrient and upwelling indicators like *Globigerina bulloides* and *Globigerinita glutinata*. These species flourish, when due to upwelling, the surface layer become rich in nutrient concentration. On the other hand, *Globigerinoides ruber* flourishes during oligotrophic condition when ocean water is well stratified. Thus relative percentage of upwelling indicators and oligotrophic species indicate the trophic level of the ocean waters. These inferences can also be tested using other geochemical proxies e.g. during high trophic level the biomass production is high leading to more organic carbon reaching the ocean sediments. Positive correlation has been observed between high abundance of *G. bulloides* and total organic carbon in the oceanic sediments\(^\text{16}\).

**Why last 5 million years?**

The late Neogene comprising Pliocene, Pleistocene and Holocene\(^\text{17}\) has been a period of conspicuous waxing and waning of ice sheets and resulting ocean circulation changes. Important changes in ocean-continent geometry including opening and closing of ocean gateways also took place during this interval which had a profound effect on the major current systems, heat transport and thus on the global climate (Closing of the Panama Isthmus\(^\text{18,19}\); Closing of the Indonesian Seaway\(^\text{5,8,11}\); opening of the Bering Strait\(^\text{20}\)). Unraveling the dynamics of the Northern Hemisphere Glaciation (NHG) in the Pliocene is a key step toward a quantitative theory of the climate transition from a greenhouse to an icehouse world\(^\text{21}\). The Pleistocene Epoch, represents an interval of abrupt climatic shifts from one boundary state to the other and this interval spanning \(\sim1.77\) million years, free from the industrialized world provides excellent opportunity to discern the dynamics of climatic changes which have not been besmirched by human influence. The period offers tremendous prospects to test the various models of climatic change by feeding paleoclimatic data obtained from undisturbed deep sea sedimentary record. Last decade has seen an enormous amount of data generated for the detailed and reliable record of surface ocean circulation changes. The late Neogene (last 5 million years) marine record offers best opportunity to study the natural climatic variability free from human influence for most of its part.

**Why eastern Indian Ocean circulation?**

The eastern Indian Ocean off Western Australia is geographically and topographically the analogue of the other eastern boundary current regions and is characterized by equatorward winds and one might expect to find broad equator ward flow and upwelling along the coast\(^\text{22}\). However the region off Western Australia behaves quite different than other eastern boundary regions. There is no regular, continuous equatorward flow within 1000 km of the coast and no evidence of coastal upwelling\(^\text{22}\). The region deserves special attention of paleoceanographers because of the fact that the area of southeast Indian Ocean off Western Australia is influenced by returning loop of the conveyor belt through Indonesian seaway, which also feeds the warm Leeuwin Current (LC) and the forward loop comprising an arm of the circum Antarctic circulation (psychrospheric circulation) in the form of West Australian Current (WAC) flowing north below the LC up to a depth of 2000 m (Fig.1). The eastern boundary of the southeast Indian Ocean is the only eastern boundary that has a direct connection to the adjacent ocean’s western equatorial region\(^\text{22}\). Weaver\(^\text{25}\) pointed out that the Leeuwin Current in a sense can be thought of as being driven by equatorial Pacific winds which pile up warm water in the Western Equatorial Pacific (WEP). The warm western equatorial Pacific waters flow through the Indonesian seaway (Fig.1) and maintain the very high geopotential anomalies (sea level) off northwestern Australia, driving Leeuwin Current\(^\text{22}\). Considering the great ocean conveyor belt, the area off Western Australia is influenced on one hand by the warm return flow of thermocline and surface waters from the Pacific via Indonesian Seaway in the form of Leeuwin Current and on the other by lower arm of the great ocean conveyor belt in the form of cold West Australian Current. Thus, the area is supposed to have recorded the history of changing ice volume in Antarctica reflected by the varying intensity of the West Australian Current, weakening and strengthening of the Leeuwin Current as a result of reduction in the Indonesian throughflow connected to the Western Pacific Warm Pool (WPWP) which in turn is related to El Nino Southern Oscillation changes (Fig.1).
Approximately 10 million m$^3$s$^{-1}$ of water flows from the Pacific Ocean into the Indian Ocean through the Indonesian Sea and the Indonesian throughflow modifies the heat and fresh water budgets and the air-sea heat fluxes of the Pacific and Indian oceans and may exercise a role in the El Nino Southern Oscillation (ENSO) and Asian Monsoon phenomenon. The WPWP, the Indonesian throughflow and the intermingling of water between the Indonesian passage and the equatorial Indian Ocean, greatly controls the oceanographic conditions in the eastern Indian Ocean. The present paper focuses on the planktic foraminiferal record generated by various workers to unravel the surface circulation history of the eastern Indian Ocean during last 5 million years.

Despite the relevance of the eastern Indian Ocean for understanding past global changes few paleoceanographic/paleoclimatic studies have been made in this region. As this region provides a linkage between the Western Pacific Warm Pool and Indian Ocean, several studies pointed out the importance of this region in controlling climate in the tropics and particularly ocean circulation off Western Australia. Most of these studies have centered on unraveling ocean circulation changes before, during and after the Last Glacial maximum (LGM). However the studies on Pliocene–Pleistocene evolution of ocean circulation from this region are few.

In the following section, ocean circulation changes, as revealed by the relative variation in abundance data of depth stratified planktic foraminiferal assemblage and stable isotope record of surface dwelling and thermocline dwelling species, has been discussed during Miocene/Pliocene transition, Early Pliocene, Late Pliocene and Pleistocene.

**Miocene/Pliocene transition and strengthening of cold west Australian current**

An intensification of cold West Australian Current towards north is manifested by a cooling of surface waters near the Miocene/Pliocene boundary based on the arrival of the temperate planktic foraminifera *Globorotalia* (*Globoconella*) *pliozea* reaching almost 5% of the total population at the eastern Indian Ocean ODP sites. The upwelling indicator species also show higher abundance during this interval which is suggestive of the cooling of surface waters and shoaling of thermocline. As discussed above, the
upwelling in modern times is suppressed by the southward flowing Leeuwin Current and thus this was also a period of weakening of the strength of the Leeuwin Current. The low abundance of the oligotrophic species group and warm mixed layer species group at the eastern Indian Ocean sites near the Miocene/Pliocene boundary also is suggestive of less stratified waters, a consequence of upwelling. The shoaling of thermocline is also evidenced by an increasing abundance of the thermocline dwelling species group near the Miocene/Pliocene boundary in the eastern Indian Ocean.

Near the Miocene/Pliocene boundary, the intensification of West Australian Current occurred as a consequence of high latitude cooling probably due to Antarctic ice sheet expansion and resultant lowering of temperature of surface waters. This interval also marks occurrence of another temperate species Neogloboquadrina pachyderma, though in very low percentage (1%).

Earlier Zachariasse found the evidence of a late Miocene climatic cooling at site 762B (Southeast Indian Ocean) based on arrival of a substantial number of specimens of the cool water species Globorotalia (Globoconella) conoidea (ancestral to G. inflata, G. punccticulata) just after the coiling change in Neogloboquadrina humerosa at site 762B. This late Miocene cooling began slightly later than 5.8 Ma and is probably related to the rapid expansion of the west Antarctic ice cap. Earlier studies have shown that toward the end of Miocene and earliest Pliocene a distinct and rapid northward movement (~300 km) occurred in the siliceous biogenic sediment belt in both the Southeast Pacific and Indian Ocean regions. This event is equated with rapid northward movement of Antarctic convergence and Antarctic surface water masses. The northward movement of the Antarctic surface water mass resulted in migration of temperate water planktic foraminifera towards north. This is attributed to a major expansion in the Antarctic ice cap at this time. Although evidence exists for Late Miocene cooling in the northern hemisphere, no evidence exists for ice sheet development until the Late Pliocene. Evidence of cooling during Miocene/Pliocene transition is also found on the eastern side of Australia. Based on the paleomagnetic stratigraphy and planktic foraminiferal studies in two marine sections of late Miocene to early Pliocene age in New Zealand, Kennett & Watkins found that the area was covered by sub Antarctic waters during much of late Miocene and early Pliocene time. Thus, the major circulation changes in the eastern Indian Ocean during Miocene/Pliocene transition was a consequence of the surface waters due to intensification in the strength of the West Australian Current and weakening of the Leeuwin Current associated with upwelling.

**Early Pliocene closing of Indonesian seaway**

Srinivasan & Sinha for the first time inferred a severing of surface water connections between the tropical Pacific and the Indian Ocean based on paleobiogeographic distribution of planktic foraminiferal genus *Pulleniatina*. The study revealed that the late Neogene planktic foraminiferal assemblages from the eastern and western side of the Indonesian seaway are very similar. The only distinct inter ocean difference however is the absence of planktic foraminiferal species *Pulleniatina spectabilis* from the Indian Ocean. This species makes its first evolutionary appearance in the equatorial Pacific at about 5.6 Ma and ranges up to 4.2 Ma. The complete absence of *Pulleniatina spectabilis* from the Indian Ocean is attributed to blocking of westward flow of tropical waters of the Pacific Ocean to the Indian Ocean resulting in a major change in ocean circulation in the tropical Pacific Ocean and Indian Ocean during 5.6-4.2 Ma. In order to understand the nature of this blockage isotopic depth ranking of *Pulleniatina spectabilis* was carried out by Srinivasan & Sinha and it was found that *Pulleniatina spectabilis* was a deep dwelling species. Thus they inferred that Indonesian Seaway became an effective biogeographic barrier to deep dwelling planktic foraminifera only while warm surface water connection was maintained throughout early Pliocene.

As a sequel to the blocking of the Indonesian Seaway and the resultant interruption of the flow of central equatorial current system of the Pacific to the Indian Ocean, the gyres circulation in the Indian Ocean strengthened. Srinivasan & Sinha believed that this strengthening of the gyral circulation might have led to intensification of the Indian Monsoon.

This closing of Indonesian seaway during Early Pliocene does not appear to have had the strength of the Leeuwin Current. Because, the warm surface circulation continued in the early Pliocene, there was no change in the strength of the Leeuwin Current, and conditions in the eastern Indian Ocean during early
Pliocene were similar to modern times. During the Early Pliocene the general abundance of the mixed layer dweller species at the eastern Indian Ocean site is spectacular. However the abundance of thermocline dweller species is generally low at both the sites. As expected the oligotrophic group also shows increasing abundance during this interval, possibly due to low trophic level of well stratified waters. Thus the planktic foraminiferal data indicates well stratified warm surface waters during the Early Pliocene in the eastern Indian Ocean.

Earlier studies have shown that During the Early Pliocene, 5 to 3 million years ago, globally averaged temperatures were substantially higher than they are today, even though the external factors that determine climate were essentially the same\(^\text{55}\). These authors summarized this early Pliocene warming as the Pliocene paradox because the intensity of sunlight incident on the Earth, the global geography, and the atmospheric concentration of carbon dioxide were essentially what they are today but surface temperatures at high latitudes were so much higher that continental glaciers were absent from the northern hemisphere and sea levels were approximately 25 m higher than today\(^\text{56}\text{-}\text{58}\).

The Early Pliocene interval thus presents before us a paleo analogue of modern time and enables us to predict the future climatic changes based on what happened during Late Pliocene and Pleistocene.

The planktic foraminiferal data for Early Pliocene from the eastern Indian Ocean suggests that a high sea level\(^\text{55}\) and absence of glaciers (which could be still contributing to rise in sea level) could have also caused a strong Leeuwin Current which is an important mechanism of supplying tropical heat towards pole in modern times. The correlation of the peak in general ocean warming with a high stand of global sea level and with pronounced excursion by tropical species into temperate seas is bipolar and well established\(^\text{59}\). Mc Gowan\(^\text{41}\) argued that such biogeographic changes were associated with an active intensified Leeuwin Current during warm interval (Miocene) in extending the limits of the Austral Indo-Pacific province. The present data is suggestive of a repetition of such conditions during early Pliocene.

### Late Pliocene and Pleistocene circulation

In general, the Late Pliocene and Pleistocene planktic foraminiferal record is distinguished by high amplitude of fluctuations from an average value in contrast to low amplitude of fluctuations in the latest Miocene and early Pliocene indicating alternation of extreme conditions in surface water paleoceanography. The most prominent feature of the Late Pliocene and Pleistocene faunal record is arrival of large populations of planktic foraminiferal species of temperate group at the eastern Indian Ocean.

![Cartoon showing surface circulation and wind patterns in the eastern Indian Ocean during Late Pliocene and Pleistocene when Leeuwin Current diminished due to lowering of sea-level and reduced Indonesian throughflow (Modified after Sinha et al\(^\text{6}\))](image)

Fig. 2—Cartoon showing surface circulation and wind patterns in the eastern Indian Ocean during Late Pliocene and Pleistocene when Leeuwin Current diminished due to lowering of sea-level and reduced Indonesian throughflow (Modified after Sinha et al\(^\text{6}\))
Indian Ocean sites\(^4\) (see Fig.2). The most prominent feature of the latest Pliocene-Pleistocene interval is clear evidence of expansion of cool surface waters probably via West Australian Current in the region of eastern Indian Ocean. This is indicated by arrival of large populations of \textit{Globoconella} group at the eastern Indian Ocean Sites\(^1\). Simultaneous with the abundance peaks of temperate planktic foraminifera, the upwelling species group is also abundant indicating the cooling of surface waters associated with upwelling due to intensified West Australian Current.

The Leeuwin current weakened and strengthened during the late Pleistocene in response to the glacial and interglacial stages at scales of 10\(^5\) years\(^1\). Divergent views were expressed regarding the weakening\(^{42}\) and strengthening\(^{43}\) of the Leeuwin current during Pleistocene to explain changes in biogeographic pattern at Southern Australian margin. Anomalously cold sea surface temperatures off Western Australia during LGM were reported by a number of workers\(^{32, 33, 60-62}\). During glacial times, the northward shifting of the subtropical convergence and associated strong offshore winds could have caused upwelling in the region\(^{33, 63}\). Major changes in ocean circulation caused by intensification in the West Australian Current and reduced strength or cessation in the flow of Leeuwin Current\(^34\) have been attributed to the cold anomaly\(^{32, 33, 60-62}\). The planktic foraminiferal data suggest that there have been several upwelling intervals during late Pliocene and Pleistocene when Leeuwin Current weekend in response to either ENSO induced changes in WPWP or due to Indonesian throughflow reduction in response to expansion of Antarctic ice sheet. \textit{Globorotalia inflata} (modern representative of \textit{Globoconella}) is regarded as a transitional water mass species preferentially found between 25\(^\circ\) and 30\(^\circ\)S in the Indian Ocean\(^{64, 65}\). Thus, at ODP sites in the eastern Indian Ocean, (20\(^\circ\)S) the way by which \textit{Globoconella} can be brought, is through cold and deep West Australian Current (WAC).

**Variations in the strength of Leeuwin Current during Late Pliocene – Pleistocene**

The possible causes for the weakening or cessation of Leeuwin Current can be understood if one looks at the principal forcing mechanism of Leeuwin Current which is generation of alongshore pressure gradients off western Australia\(^{36}\) linked to Western Pacific Warm Pool and Indonesian throughflow\(^{23}\). Weaver\(^{23}\) pointed out that Leeuwin Current can be thought of as being driven by equatorial Pacific winds which pile up warm water in the Western Equatorial Pacific. The warm western equatorial Pacific waters through the Indonesian Archipelago flow and maintain very high geopotential anomalies (sea level) off northwestern Australia. Thus the Leeuwin current would shut down if there is either diminution in the Western Pacific Warm Pool or there is sea level lowering due to cooling and ice build up. Studies have shown that the Leeuwin Current was significantly reduced during the LGM\(^{36}\). Because the upwelling events of early Late Pliocene are not associated with any northward transport of cool waters (Low abundance or absence of temperate planktic foraminifera) it is suggested that these upwelling events have been due to weakening of the Leeuwin Current as a result of reduction in the Western Pacific Warm Pool due to El Niño conditions. The relationship between Leeuwin Current and El Niño event is such that it is weak during ENSO conditions\(^{46, 67}\). During these upwelling events, it is believed that Leeuwin Current diminished due to the ENSO induced lowering of sea level in the Western Pacific Warm Pool and resulting dominance of equatorward wind driven circulation resulting into offshore Ekman transport, similar to the Peruvian coast. The decrease in WPWP is a reasonable explanation as it would result in decrease in alongshore pressure gradient which is the principal mechanism forcing the Leeuwin Current poleward against the prevailing equatorward winds. Thus variations in the strength of the Leeuwin current can be regarded as a good monitor for inferring past El Niño conditions.

The weakening of the Leeuwin Current (LC) would have an effect on the sea surface temperature in the Indian Ocean because the role of the Indonesian throughflow is to warm the Indian Ocean. Thus the intervals represented by intense upwelling could probably be the intervals of lowering of SST in the Indian Ocean and would definitely have influenced Indian monsoon intensity. In this context it can be said that during the weak LC there is a possibility of reduced intensity of Indian Winter Monsoon and strong summer Monsoon because of change in the Indian Ocean dipole due to reduction in net heat input to the Indian Ocean through Indonesian throughflow (ITF).

**Conclusion**

The circulation in the eastern Indian Ocean during last five million years can be summarized as

1. A late Miocene weakening of the Leeuwin...
Current and strengthening of the west Australian Current in response to expansion of the Antarctic ice sheet.

2. Early Pliocene closing of the Indonesian Seaway to deep thermocline waters and only surface warm mixed layer connections maintained. Strengthening of the warm Leeuwin Current and rise in sea surface temperature in Indian Ocean which might have led to intensification of the Indian Monsoon.

3. Late Pliocene-Pleistocene fluctuation in the strength of the Leeuwin Current either due to El Nino or due to large scale fluctuation in the Antarctic ice cap formation. Based on variation in the relative abundance of key planktic foraminiferal species and oxygen isotopic record Sinha et al. identified five intervals during the Quaternary at 2.22Ma (PL-1), 1.83 Ma (PL-2), 0.68 Ma (PL-3), 0.45 Ma (PL-4) and 0.04 Ma (PL-5) when the sea off western Australia underwent intense upwelling (PL-3 to PL-5) and moderate upwelling (PL-1 and PL-2) in contrast to modern Oceanographic conditions due to weakening or cessation of the flow of Leeuwin Current. The PL-1 and PL-2 events of upwelling were attributed by Sinha et al. to El Nino induced reduction in Western Pacific Warm Pool and weak Leeuwin Current while the PL-3, PL-4 and PL-5 events were ascribed to upwelling and weakening of Leeuwin Current due to reduced Indonesian throughflow due to lowering of sea level in response to ice volume increase. These periods of weak Leeuwin Current are the intervals of reduced net heat inflow into the Indian Ocean from the Pacific via Indonesian Seaway and thus would have resulted in reduced sea surface temperature in the Indian Ocean and reduced winter monsoon intensity.

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