The tropical warm pool in the Indian Ocean and its influence on ENSO over the past 137,000 yrs BP

R. Saraswat[1,*], R. Nigam[1], S. Weldeab[2,4] and A. Mackensen[3]

[1]Micropaleontology Laboratory, National Institute of Oceanography, Dona Paula, Goa 403 004, India
[2]Geosciences, Bremen University, Research Center Ocean Margins, 28357 Bremen, Germany
[3]Alfred Wegener Institute for Polar and Marine Research, Columbusstrasse, D-27568 Bremerhaven, Germany
[4]Present address: Department of Geological Sciences, University of California, Santa Barbara, USA

The tropical sea surface temperature (SST) is one of the important factors that regulates the amount and duration of rainfall in the tropical region, the world's most densely populated region. The tropical oceanic warm pool today extends across the Pacific and Indian oceans. The geographic extent of warm pool shows annual variability, leading to changing east-west gradients in tropical SST that contribute to El-Nino Southern Oscillation (ENSO) and other related processes of the tropical circulation. From the magnesium–calcium analysis of planktic foraminifera, we reconstructed SST in the Indian Ocean over the past 137,000 years, providing a new reconstruction of the changing extent of the warm pool, the east-west gradients and their influence on ENSO through time. Comparison of our results with those from the Pacific Ocean, shows that throughout the larger part of the last ~137 ka BP, equatorial Indian Ocean (EIO) was the warmest part of the tropics. However, the eastern Pacific Ocean (EEP) was warmer than both the western Pacific Ocean (WEP) and EIO for a brief period during penultimate glacial–interglacial transition. The SST difference between EIO and EEP as well as between WEP and EEP shows strong positive correlation over the entire period of ~137 ka BP, suggesting that during the large part of the past glacial period, more intense and frequent El-Nino-like conditions persisted and influenced the tropical Indian and Pacific oceans.

Keywords: El-Nino, tropical region, sea surface temperature, warm pool.

TODAY, the tropical western Pacific contains the warmest water, and is an important reservoir of heat on the planet. The modern sea surface temperature (SST) in regions of the tropical Indian Ocean also remains consistently high throughout the year, thus making it a part of the world oceanic warm pool[1], a feature responsible for active convection[2,3]. Upwelling along the African coast bringing up cooler water, absence of upwelling along the eastern margin of Indian Ocean, and eastward surface currents in the equatorial Indian Ocean lead to SST increasing towards the east, a SST gradient in contrast with the other world oceans[4,5]. Combined Indo-Pacific Warm Pool (IPWP) is an essential component of global ocean and atmospheric circulation, and slight change in intensity and geographic extent of IPWP results in global climatic changes[6]. Though SST over the Indian Ocean in general shows large-scale seasonal variability, SST variation in the eastern equatorial Indian Ocean (EIO)[7] remain within ~± 0.5°C. Based on the surface and subsurface temperature variation in the eastern EIO and the equatorial western Pacific Ocean (WEP), it has been suggested that the Indian Ocean Warm Pool (IOWP) and the Western Pacific Warm Pool (WPWP) are part of a single water mass[1]. Transport of significant amount of mass, heat and freshwater into the eastern Indian Ocean from the WEP, through the Indonesian archipelago has been suggested to control SST variation in the eastern Indian Ocean[8–10]. However, Loschnigg and Webster[11] concluded that the factors regulating SST in the Pacific and Indian oceans are altogether different, with local thermodynamic balance and large-scale atmospheric circulations playing the major role in controlling SSTs in the Pacific, with the northern Indian Ocean SSTs being regulated by strong oceanic advection across the equator and by changes in heat storage of the upper ocean. Thus, the effect of the Pacific Ocean SST variation over SST of the EIO and also in interannual variability in monsoon strength is being debated[12–14]. Though Saji *et al.*[15] and Webster *et al.*[4] noted the possible influence of internal dynamics (Indian Ocean dipole) in regulating SST and rainfall in the EIO region, Shinoda *et al.*[16] showed good correlation between surface temperature variation in the Indian Ocean region and the El-Nino Southern Oscillation (ENSO). Lately, it has also been suggested that the relationship between the Indian monsoon and the ENSO is not convincing[17].

Therefore, understanding the link, if any, between SST variation in the Indian and the Pacific oceans, will help in better prediction of future monsoon changes in the Indian subcontinent. Though possible existence of the ENSO and the link between the ENSO and climatic variations in the Atlantic region during the geologic past have been reconstructed[18,19], limited attempts have been made to infer such a link between the EIO SST variation and the ENSO[20]. Recognizing the importance of the Indian Ocean as part of the tropical warm pool, we reconstructed the EIO SST for the last ~137 ka BP and compared it with the Pacific Ocean SST variation[21].

In order to reconstruct past SSTs from the EIO, Mg/Ca analysis was carried out on the top 270 cm of a core (SK 157/4) collected from the eastern flank of the Comorin ridge (Figure 1; 02°40′N, 78°00′E, water depth 3500 m). Mg/Ca analysis was performed on surface-dwelling planktic foraminifer species, *Globigerinoides ruber* (white) that has been demonstrated to reliably record SST. The chrono-

*For correspondence. (e-mail: rs.niog@gmail.com)

logy for the upper part of the core is based on accelerator mass spectroscopy (AMS) and conventional radiocarbon dates carried out at Leibnitz Laboratory, Kiel, Germany, and Birbal Sahni Institute for Palaeobotany, India, respectively. The chronology was extended down to ~137 kyr by tuning the $\delta^{18}O$ ratio of *G. ruber*, measured at Alfred Wegener Institute for Polar and Marine Research, Bremerhaven, Germany, to the low-latitude isotopic stack of Bassinot *et al.*[22]. The detailed methodology has been published elsewhere[23].

The core-top SST reconstructed from Mg/Ca analysis (~28.1°C) matches reasonably well with the modern annual average SST (~28.5°C) at the core location[7]. The down-core variation of Mg/Ca SST shows that the EIO was ~2.1°C cooler during the Last Glacial Maximum compared to the Present. The difference between minimum and maximum SST during the last ~137 ka BP is highest in EEP (~7.5°C), whereas it is comparable in the WEP and EIO (~3.7°C and ~3.8°C respectively; Figure 2). The glacial–interglacial SST contrast during the last glacial–interglacial transition is slightly lower in the EIO (~2.1°C) compared to the SST contrast over the same period in both WEP (~2.8°C) and EEP (~2.6°C). Down-core plot of SST difference between WEP and EIO shows that during the larger part of the last ~137 ka BP, EIO was either equally warm or warmer than WEP (Figure 3), in contrast to the warmer WEP (~0.50°C) at present[7]. The SST difference between WEP and EIO increased significantly (~ –1.7°C) just after the penultimate interglacial. The SSTs in WEP and EIO were comparable during the period from ~106 till ~58 ka BP, the beginning of isotopic stage 3. Throughout the isotopic stage 3, the WEP was cooler than the central EIO and remained so till the last glacial–interglacial transition. WEP was comparatively warmer during the beginning of the present as well as penultimate interglacial periods. The pattern of increase in WEP SST shows similar trend during both present and penultimate glacial–interglacial transition with WEP becoming warmer than EIO during the beginning of glacial–interglacial transition.

Interestingly, the timing and pattern of difference in SST between WEP and EEP, and between EIO and EEP, show strong positive correlation ($r^2 = 0.78$) significant at 99.9% level of significance, during the last ~137 ka BP (Figure 4).

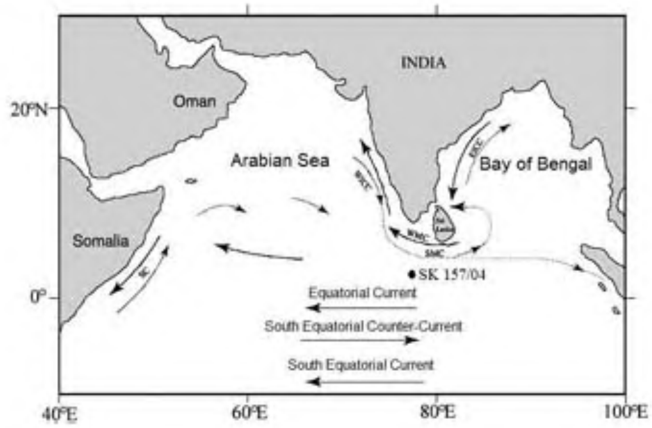

Figure 1. Core location with winter and summer monsoon surface sea-water circulation (solid and dotted curved arrows respectively). WICC, West Indian Coastal Current; EICC, East India Coastal Current; SC, Somali Current; SMC, Summer Monsoon Current, and WMC, Winter Monsoon Current.

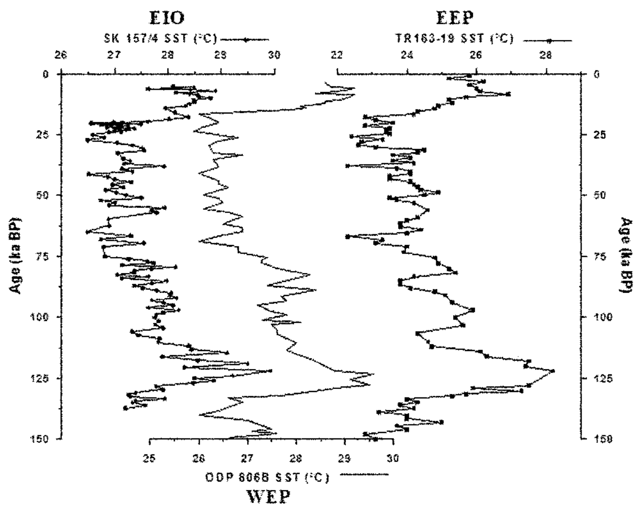

Figure 2. Mg/Ca-based SST variation from the central equatorial Indian Ocean (SK 157/4) and eastern and western Pacific Ocean (TR 163-19 and ODP 8O6 B respectively)[21] over the last ~137 ka BP.

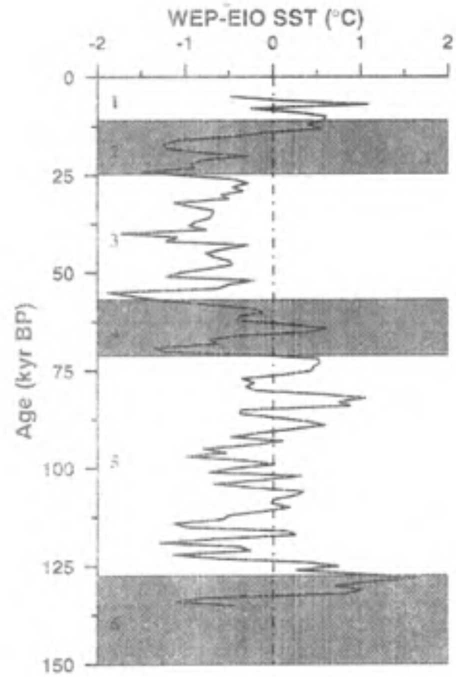

Figure 3. SST difference between western equatorial Pacific Ocean (WEP) and central equatorial Indian Ocean (EIO). Dotted line shows zero SST difference between WEP and central EIO. Numbers and alternate shaded zones mark isotopic stages.

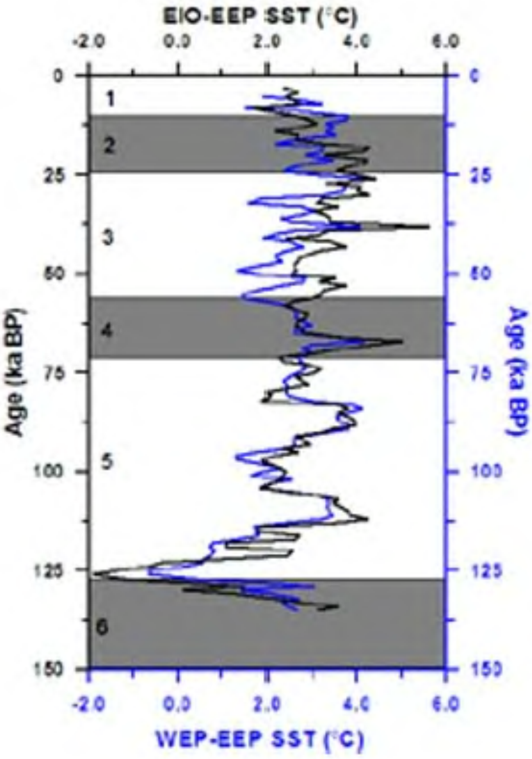

Figure 4. SST difference between central EIO and eastern equatorial Pacific Ocean (EEP) as well as between WEP and EEP. Except during the penultimate interglacial period (~123 ka BP), the EEP has always remained cooler than the EIO and WEP. The down-core variation of SST difference between EIO and EEP as well as between WEP and EEP shows strong positive correlation (0.78).

However, the amplitude of SST difference between EIO and EEP shows large variation, especially during the period prior to penultimate glacial–interglacial transition. The SST difference between EIO and EEP as well as between WEP and EEP remains positive (varying from ~1.3°C to ~4.5°C), throughout the core, except during penultimate glacial–interglacial transition. During penultimate glacial–interglacial transition, the difference decreases to –0.6°C for WEP–EEP and –1.9°C for the EIO–EEP. This negative SST difference between WEP and EEP as well as between EIO and EEP during penultimate glacial–interglacial transition period indicates that the EEP was warmer than both the WEP and EIO during penultimate glacial–interglacial transition. From ~107 ka BP onwards till the termination of isotopic stage 4, the difference in SST between EIO and EEP as well as between WEP and EEP was similar. During the isotopic stages 3 and 2, the SST difference between EIO and EEP was comparatively higher than the SST difference between WEP and EEP. However after the last glacial–interglacial transition, the SST difference between EIO and EEP as well as between WEP and EEP again became comparable.

Possible implication of increased SST in the central EIO can be a more intense El-Nino since during El-Nino, the western limb of the Walker Cell, the zone of active convective heating, shifts eastward in the Pacific Ocean[12]. The eastward movement of western limb of the Walker Cell results in decreased convective heating in the western Pacific leading to the relatively cooler SST in WEP and increased SST in EEP, and lighter than average winds over the Indian Ocean[24]. Comparatively weakened winds over the Indian Ocean will result in reduced transport of cooler water towards the Bay of Bengal through weakened southwest monsoon current[25], thus further increasing SST in the central EIO. Numerous studies have reported reduced southwest monsoon strength during the last glacial period[26–29]. At the same time, the SST gradient in the EIO will decrease as the eastern EIO will no longer be as warm as under non El-Nino (or La-Nina) condition due to lighter-than-average winds that occur over the Indian Ocean during El-Nino[24]. The overall warming of the Indian Ocean during the El-Nino events, with positive values in the western EIO and negative anomalies in the eastern EIO, has previously been noted by Tiwari *et al.*[30] on the basis of SST records of the Indian Ocean during the last 40 years. Nicholson[31] and Chambers *et al.*[32] also observed warming in the Indian Ocean during the El-Nino events. Under such condition, SST difference between WEP and central EIO will be more negative as seen in Figure 2, whereas SST difference between WEP and EEP will decrease as observed in Figure 3. However SST difference between the central EIO and EEP will depend on the response of EEP to the eastward shifting of the core of the WPWP. Considering the comparatively large distance between the WEP and EEP, the amplitude of EEP warming is expected to be comparatively less, leading to increased SST difference between EIO and EEP (Figure 4).

Based on Mg/Ca analysis of planktic foraminifera, we conclude that for the large part of the past ~137,000 yrs BP, the Indian Ocean was equally warm or warmer than the equatorial Pacific Ocean. However, for a brief period during penultimate glacial–interglacial transition, EEP was the warmest of the tropical region. SST contrast between EIO and the Pacific Ocean was highest during the glacial–interglacial transitions. We further propose that during the large part of the past glacial period, more intense and frequent El-Nino-like conditions persisted and influenced SSTs of both the Indian and Pacific oceans. However, SST reconstruction from both eastern and western EIO will help in further understanding the factors regulating SST variation in the Indian Ocean and possible link between SST variation in the Pacific and Indian oceans.

1. Vinayachandran, P. N. and Shetye, S. R., The warm pool in the Indian Ocean. *Proc. Indian Acad. Sci.* (*Earth Planet. Sci.*), 1991, **100**, 165–175.
2. Gadgil, S., Joseph, P. V. and Joshi, N. V., Ocean–atmosphere coupling over monsoon regions. *Nature*, 1984, **312**, 141–143.
3. Graham, N. E. and Barnet, T. P., Sea surface temperature, surface wind divergence and convection over tropical oceans. *Science*, 1987, **238**, 657–659.

4. Webster, P. J., Moore, A. M., Loschnigg, J. P. and Leben, R. R., Coupled ocean–atmosphere dynamics in the Indian Ocean during 1997–98. *Nature*, 1999, **401**, 356–360.
5. Konda, M., Imasato, N. and Shibata, A., Interannual variability of the sea-surface temperature in the Indian Ocean in response to the air–sea turbulent heat exchange. *Deep-Sea Res.*, 2002, **49**, 1527–1548.
6. Gagan, M. K., Hendy, E. J., Haberle, S. G. and Hantoro, W. S., Post-glacial evolution of the Indo-Pacific Warm Pool and El Nino-Southern oscillation. *Quat. Int.*, 2004, **118–119**, 127–143.
7. *Levitus Climatology*, 1994; http://kadamba.nio.org/fbin/climate_server.
8. Fine, R. A., Direct evidence using tritium data for throughflow from the Pacific into the Indian Ocean. *Nature*, 1985, **315**, 478–480.
9. Wijffels, S., Sprintall, J., Fieux, M. and Bray, N., The JADE and WOCE I10/IR6 throughflow sections in the southeast Indian Ocean. Part 1: Water mass distribution and variability. *Deep-Sea Res.*, 2002, **49**, 1341–1362.
10. Sprintall, J., Potemra, J. T., Hautala, S. L., Bray, N. A. and Pandoe, W. W., Temperature and salinity variability in the exit passages of the Indonesian throughflow. *Deep-Sea Res.*, 2003, **50**, 2183–2204.
11. Loschnigg, J. and Webster, P. J., A coupled ocean–atmosphere system of SST regulation for the Indian Ocean. *J. Climate*, 2000, **13**, 3342–3360.
12. Webster, P. J. and Yang, S., Monsoon and ENSO: Selectively interactive systems. *Q. J. R. Meteorol. Soc.*, 1992, **118**, 877–926.
13. Ropelewski, C. F., Halpert, M. S. and Wang, X., Observed tropospheric biennial variability and its relationship to the Southern Oscillation. *J. Climate*, 1992, **5**, 594–614.
14. Joseph, P. V., Eischeid, J. K. and Pyle, R. J., Interannual variability of the onset of the Indian summer monsoon and its association with atmospheric features, El-Nino, and sea surface temperature anomalies. *J. Climate*, 1994, **7**, 81–105.
15. Saji, N. H., Goswami, B. N., Vinayachandran, P. N. and Yamagata, T., A dipole mode in the tropical Indian Ocean. *Nature*, 1999, **401**, 360–363.
16. Shinoda, T., Hendon, H. H. and Alexander, M. A., Surface and subsurface dipole variability in the Indian Ocean and its relation with ENSO. *Deep-Sea Res.*, 2004, **51**, 619–635.
17. Kumar, K. K., Rajagopalan, B. and Cane, M. A., On the weakening relationship between the Indian monsoon and ENSO. *Science*, 1999, **284**, 2156–2159.
18. Tudhope, A. W. *et al.*, Variability in the El Nino-Southern Oscillation through a glacial–interglacial cycle. *Science*, 2001, **291**, 1511–1517.
19. Turney, C. S. M., Kershaw, A. P., Clemens, S. C., Branch, N., Moss, P. T. and Fifield, L. K., Millennial and orbital variations of El Nino/Southern Oscillation and high-latitude climate in the last glacial period. *Nature*, 2004, **428**, 306–310.
20. Cole, J. E., Dunbar, R. B., McClanahan, T. R. and Muthiga, N. A., Tropical Pacific forcing of decadal SST variability in the western Indian Ocean over the past two centuries. *Science*, 2000, **287**, 617–619.
21. Lea, D. W., Pak, D. K. and Spero, H. J., Climate impact of late Quaternary equatorial Pacific sea surface temperature variations. *Science*, 2000, **289**, 1719–1724.
22. Bassinot, F. C., Labeyrie, L. D., Vincent, E. X. Q., Shackleton, N. J. and Lancelot, Y., The astronomical theory of climate and the age of the Brunhes–Matuyama magnetic reversal. *Earth Planet. Sci. Lett.*, 1994, **126**, 91–108.
23. Saraswat, R., Nigam, R., Weldeab, S., Mackensen, A. and Naidu, P. D., A first look at past sea surface temperatures in the equatorial Indian Ocean from Mg/Ca in foraminifera? *Geophys. Res. Lett.*, 2005, **32**, L24605.
24. Webster, P. J., Magana, V. O., Palmer, T. N., Shukla, J., Tomas, R. A., Yanai, M. and Yasunari, T., Monsoons: Processes, predictability and the prospects for prediction. *J. Geophys. Res.*, 1998, **103**, 14451–14510.
25. Vinayachandran, P. N., Masumoto, Y., Mikawa, T. and Yamagata, T., Intrusion of the southwest monsoon current into the Bay of Bengal. *J. Geophys. Res.*, 1999, **104**, 11077–11085.
26. Clemens, S. C., Prell, W. L., Murray, D., Shimmield, G. and Weedon, G., Forcing mechanisms of the Indian Ocean monsoon. *Nature*, 1991, **353**, 720–725.
27. Prell, W. L. and Kutzbach, J. E., Sensitivity of the Indian monsoon to forcing parameters and implications for its evolution. *Nature*, 1992, **360**, 647–652.
28. Anderson, D. M. and Prell, W. L., A 300 KYR record of upwelling of Oman during the late Quaternary: Evidence of the Asian southwest monsoon. *Paleoceanography*, 1993, **8**, 193–208.
29. Hong, Y. T. *et al.*, Inverse phase oscillations between the East Asian and Indian Ocean summer monsoons during the last 12,000 years and paleo-El Nino. *Earth Planet. Sci. Lett.*, 2005, **231**, 337–346.
30. Tiwari, V. M., Cabanes, C., DoMinh, K. and Cazenave, A., Correlation of interannual sea level variations in the Indian Ocean from Topex/Poseidon altimetry, temperature data and tide gauges with ENSO. *Global Planet. Change*, 2004, **43**, 183–196.
31. Nicholson, S. E., An analysis of the El Nino signal in the tropical Atlantic and western Indian oceans. *Int. J. Climatol.*, 1997, **17**, 345–375.
32. Chambers, D. P., Tapley, B. D. and Stewart, R. H., Anomalous warming in the Indian Ocean coincident with El-Nino. *J. Geophys. Res.*, 1999, **104**, 3035–3047.

ACKNOWLEDGEMENTS. Financial support from the Department of Ocean Development, New Delhi is acknowledged. We thank Dr M.-J. Nadeau, Leibnitz Laboratory, Kiel, Germany; Dr B. Sekar, Birbal Sahni Institute for Palaeobotany, Lucknow, and Dr J. E. Noakes, Center for Applied Isotopic Studies, Athens for providing radiocarbon dates. We also thank Drs D. V. Borole and V. Ramaswamy, National Institute of Oceanography, Goa for help at various stages; Dr D. M. Anderson, NOAA Paleoclimatology Branch Chief and Director, World Data Center for Paleoclimatology, USA; Dr R. K. Tiwari, National Geophysical Research Institute, Hyderabad and Dr P. N. Vinayachandran, Indian Institute of Science, Bangalore for constructive comments and suggestions on the manuscript. R.S. acknowledges financial support from the Council of Scientific and Industrial Research, New Delhi and UGC–DAAD, New Delhi, in the form of Senior Research Fellowship and Short-term DAAD Fellowship respectively.

Received 8 May 2006; revised accepted 27 November 2006