

## Supra-generic radiolarian transfer function based late Miocene paleomonsoonal changes in the northeastern tropical Indian Ocean

Shyam M. Gupta and A.A. Fernandes

National Institute of Oceanography, Dona-Paula, Goa 403 004, India

### Abstract

A Q-mode factor analysis of the % data of 25 broadly defined supra-generic radiolarian groups in 42 deep-sea surface sediments produced four statistically significant and geographically distinct faunal assemblages related to (i) southwest cooler ( $< 27^{\circ}\text{C}$ ), hypersaline ( $> 34.5\text{ppt}$ ) and highly productive ( $> 0.3 \text{ mgC/m}^3/\text{d}$ ); (ii) northeastern warmer ( $> 27^{\circ}\text{C}$ ), hyposaline ( $< 34.5\text{ppt}$ ) and poor productive ( $< 0.2 \text{ mgC/m}^3/\text{d}$ ); (iii) transitional and (iv) southern water masses during southwest monsoon in the central tropical Indian Ocean. The southwest hypersaline and northeast hyposaline faunal assemblages are separated by a transitional assemblage that divides the central Indian Ocean basin diagonally along the 34.5ppt isohaline south of Sri Lanka. The southern factor dominates the area influenced by the  $10\text{-}12^{\circ}\text{S}$  hydrographic front. Factor value of these assemblages were regressed onto modern sea surface temperature (SST), salinity and potential primary productivity (PPP) of surface waters overlying each sample locations. Resultant transfer functions have multiple correlation coefficients ( $r$ ) at 0.001 level of significance (99.9%) for the salinity, PPP and SST for the southwest monsoon only. Descending trend in the correlation coefficients for the salinity-July-August ( $r=0.834$ ), PPP-SWM ( $r=0.785$ ) SST-spring (May-July) ( $r=0.695$ ) suggests order of the faunal sensitivity in the area and their respective reliabilities in the paleoestimates. The transfer functions produced comparable estimates of the observed value for the majority within the limits of standard errors of estimated salinity, SST and PPP changes using % data of the late Miocene radiolarian sequence from the Sawai Bay Formation, Neill Island, Andamans. Estimated SST and salinity during southwest monsoon are not only conformable with the qualitative paleoceanography in terms of warmer periods (W) of W-9 and W-11, but also have resolved W-8 and W-10 in late Miocene Neill Island radiolarian data-set. Salinity minima in warmer and maxima in colder periods reflect the influx of fresh water from the Ganges-Brahmaputra rivers into the Bay of Bengal during southwest monsoon. The lowering trend in spring-salinity from 9.0-5.0 million years suggest the gradual strengthening of the monsoon system. The results substantiate the hypothesis that monsoonal conditions prevailed during the late Miocene.

### Introduction

Recent studies suggest that the Asian monsoon originated with the attainment of half of the present altitude of Himalayan-Tibetan plateau during the late Miocene, which caused a natural barrier that changed non monsoonal to monsoonal atmospheric circulation in the northern Indian Ocean (Ruddiman and Kutzbach, 1991; Prell *et al.*, 1992). Although, the monsoon is an atmos-

pheric phenomenon, it has a pronounced effect on the Indian Ocean surface waters. The Ganges-Brahmaputra rivers discharge enormous fresh water ( $90 \times 10^3 \text{ m}^3/\text{s}$ ) during July-August, which is the peak period of the southwest monsoon (Carroll *et al.*, 1993), into the Bay of Bengal resulting in the lowering of the surface salinity of the northeastern Indian Ocean (Wyrtki, 1971; Levitus, 1982). Further west towards the Arabian Sea, however, the surface water remains

comparatively hypersaline ( $> 34.5$  ppt) because of the regional positive evaporation-precipitation budget (Clemens *et al.*, 1991) and the absence of riverine fresh-water influx. Because the majority of radiolaria inhabit the top 100 m of oceanic water (Dworetzky and Morley, 1987), they register salinity changes in surface waters. Therefore, radiolaria preserved in sediments may retain a paleomonsoonal record that can be estimated by using transfer function technique since late Miocene.

Radiolarian transfer functions have been widely used to estimate late Quaternary oceanographic changes in the Pacific (Moore *et al.*, 1980), Atlantic and southern ( $> 20^\circ$  S) Indian Ocean (Morley, 1979, 1989). Because of inadequacy in % data from surface sediments (Lombardi and Boden, 1985) there are no radiolarian transfer functions in the northern (north of  $20^\circ$  S) Indian Ocean. Moreover, previous studies are based on extant species/groups with the assumption that fauna have not undergone significant evolutionary change over the last one million years (Ma). Although, the census date of extant species has the advantage during the late Quaternary, it has the disadvantage that relationships between species variations and environment cannot be applied beyond the stratigraphic and geographic limits of strictly defined taxa (Mullineux and Westberg-Smith, 1986). It constrained the use of earlier transfer functions in the late Miocene samples, but the same can be worked out by the supra-generic approach. How the sea surface temperature (SST) and salinity have changed from late Quaternary to late Miocene is not known because of the absence of supra-generic transfer function in the northern

Indian Ocean. However, such studies have already been carried out in the Pacific Ocean (Moore and Lombardi, 1981; Romine, 1985; Hayes *et al.*, 1989). Our objective was to derive such supra-generic transfer functions and to produce reliable numerical values of the oceanic changes. Resultant paleoestimates would be more accurate than a qualitative approach in terms of warmer-humid and colder-arid climatic scenario in the late Miocene.

### Oceanographic Setting

The tropical Indian Ocean exhibits seasonal changes in surface water during the northeast and southwest monsoons (Wyrtki, 1971). SST and salinity exhibit strong seasonal changes in the tropical Indian Ocean. SST variation in December (SST-Dec.) is low ( $3^\circ\text{C}$ ,  $26-29^\circ\text{C}$ ) compared to high ( $6^\circ\text{C}$ ,  $23-29^\circ\text{C}$ ) in August (SST-Aug.) in the area north of  $20^\circ$  S (Fig. 1a-b). Between  $10^\circ$  N to  $4^\circ$  S, SST vary from  $29-28^\circ\text{C}$ , but south of  $4^\circ$  S to  $20^\circ$  S, SST gradient is higher ( $28-23^\circ\text{C}$ ) with isotherms subparallel to the latitudes during August (Fig. 1b). Between  $4^\circ$  S to  $20^\circ$  S surface water is  $1-4^\circ\text{C}$  cooler compared to the northern part, north of  $4^\circ$  S, during August. Because of enormous monsoonal fresh water influx from the Ganges-Brahmaputra rivers ( $90 \times 10^3 \text{ m}^3/\text{s}$ ) during July-August, the peak period of SW monsoon (Carroll *et al.*, 1993), the surface water is hyposaline ( $< 34.5$  ppt) toward the Bay of Bengal; whereas it remains hypersaline ( $> 34.5$  ppt) due to positive evaporation value in the Arabian-Sea side (Wyrtki, 1971). Salinity varies from 32-34.5 ppt and 34.5-35.5 ppt in the east and west respectively during NE monsoon (Fig. 1c). Salinity contrast that

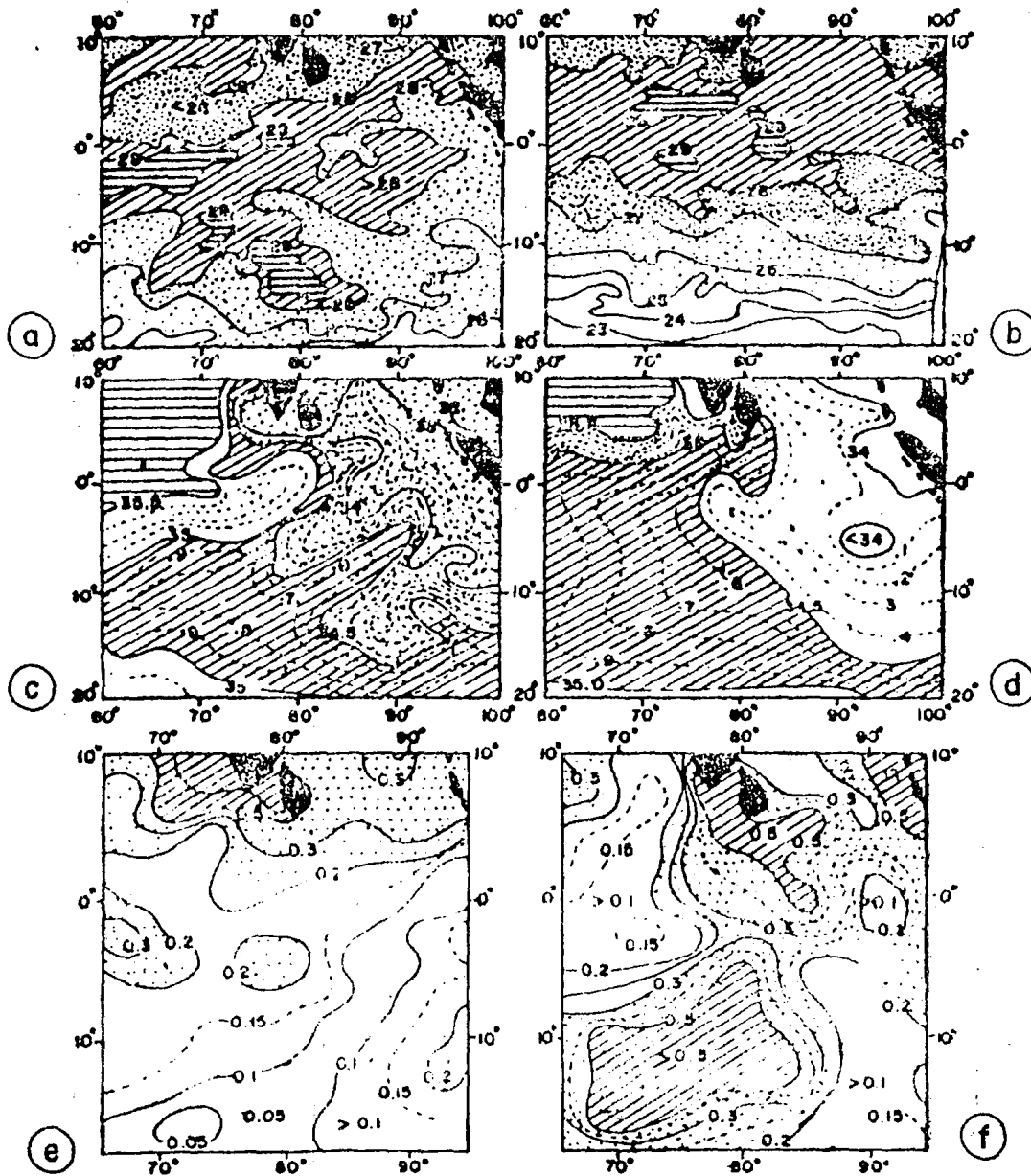


Fig. 1. Seasonal surface-water oceanographic parameters used to relate the factors in present study. (a) SST-Dec., (b) SST-Aug., (c) salinity-Nov.-Dec., (d) salinity-July-Aug. [after Wyrtki, 1971]; and potential primary productivity ( $\text{mgC}/\text{m}^3/\text{d}$ ) in NE monsoon (e) SW monsoon (f) [after Krey and Habenerd, 1976] in the central tropical Indian Ocean.

divides the basin obliquely along the 34.5ppt isohaline south of Sri Lanka into south-western and northeastern parts during July-August (Fig. 1d) is more pronounced. A marked hydrographic front at 10-12°S, characterized by lower salinity, low primary productivity and nutrient content, extends across the equatorial Indian Ocean from Sumatra to Somalia (Wyrtky, 1973). Similarly, surface water potential primary productivity (PPP) is higher during southwest monsoon than in the northeast monsoon (Figs. 1e-f).

## Material and Methods

### Selection of Surface Sediment Samples

The surface sediments (top of the seafloor) were selected following the criteria of Imbrie and Kipp (1971). Sediments collected by small grab samples especially designed to collect top-layer of ~ 10 cm (personal communication, A.V. Sonawane) were found suitable as a fluid top layer (2-3 cm) indicator of sediment-water interface of the Holocene age was invariably present. Out of 57, only 4 surface sediments (Fig. 2, Table 1) were selected from the central Indian Basin for the analysis after discarding the dubious Holocene samples with fossil radiolaria or the anomalous fauna from the neighbouring samples. Based upon the average sedimentation rates of ~ 1 cm/kilo-year (Ka) reported by Johnson *et al.*, (1989) for the top most sections of the core VM-34-53 at Lat. 10°29'S, Long. 78°03'E (0-236 cm=210 Ka) and RC-14-22 at Lat. 11°28'S, Long. 75°09'S (0-100 cm=120 Ka), our samples are representative of Holocene material. We followed Moore's (1973a) method to quantify our radiolarian data. Late Miocene radiolarian data on coarser taxonomy of Gupta and Srinivasan (1992)

was used for the paleoestimates.

### Supra-Generic Radiolarian Categories

To study the oceanographic changes since late Miocene, it was necessary to construct a data-base of modern radiolaria using more general characteristics that have not changed with time by discounting minor changes in the morphology of a species or genera. It needed a scheme that accounted for the characters in modern species groups and fossil counterparts since late Miocene for the northern Indian Ocean, which is well defined and illustrated in Gupta (1991) and Gupta and Srinivasan (1992). Such broadly-defined coarser taxonomic groups have already been used for qualitative paleoenvironmental changes (Riedel *et al.*, 1985; Mullineaux and Westberg-Smith, 1986; Gupta and Srinivasan, 1992). Recent studies show that the closer morphology of radiolarian generic-pairs develop lesser niches in their seasonal fluxes in sediment traps (Takahashi, 1987), and the subfamily, family and suborder level census data yield nearly similar results to the one based on species (Boltovskoy, 1987). These studies suggested that the distribution of high level (broadly-defined) radiolarian categories (groups) are meaningful in ecological terms and provided impetus to the logics behind the coarser taxonomy based supra-generic radiolarian transfer in present study.

Although, 250 radiolarian species were present in surface samples, the census data was generated on broadly-defined taxonomic groups (here after, groups) that are defined and illustrated in Gupta (1991) and Gupta and Srinivasan (1992). Identification of species, construction of groups in modern sediments from the central Indian Ocean basin and late Miocene Neill Island, and the

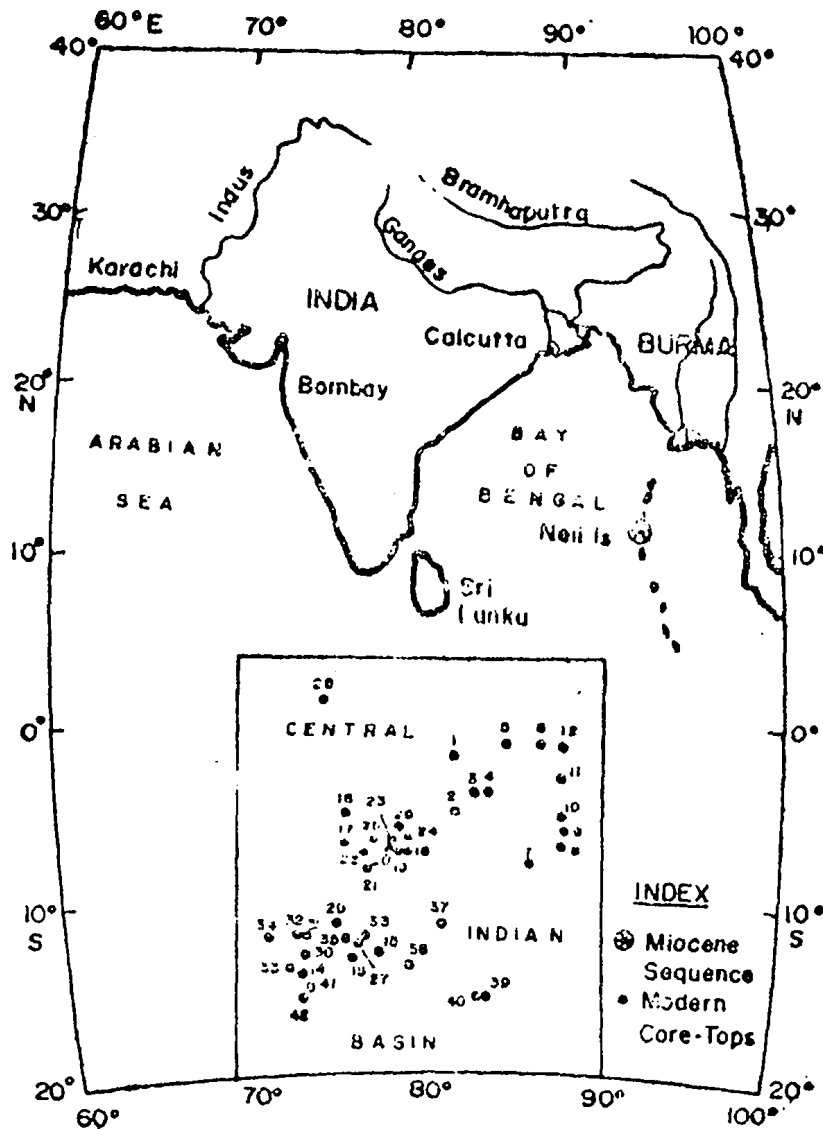


Fig. 2. Locations of the surface sediments in the central Indian Basin and the late Miocene samples locality in the northeastern Indian Ocean. Litho and biostratigraphic details of the late Miocene sequence of Sawal Bay Formation may be referred in Gupta and Srinivasan (1992).

counting was performed. We discriminately analyzed and selected analogous radiolarian groups that were common in modern surface sediments and in the late Miocene data sets. As the deep and intermediate dweller radiolarian groups (Gupta and Srinivasan, 1992,

Plectopyramidins, *Botryostrobus*, *Sethoperinids*, and *Siphocampe*) do not represent surface water characteristics, they were omitted in the present analysis. Out of 47 groups, only 25 could qualify >2%, surface to near surface and modern analogue criteria

Table 1. Latitudes, Longitudes, water depths, sampling devices and factor loading matrix for 42 modern surface samples in the Central Indian Basin.

S.M. no.	Sample no.	Latitudes	Longitudes	Depth (m)	Sampler used	Commun- nality	Southwest (F1)	Northeast (F2)	Transition- oral (F3)	Southern (F4)	
1.	RVG 2483	02.050 S	82.070 E	4590	PG	.86144	-.47741	-.65004	-.44852	.69893	
2.	RVG 2485	05.000 S	82.070 E	4990	PG	.87629	-.38317	-.70603	-.40199	.25349	
3.	RVG 2494	04.000 S	83.190 E	3750	PG	.86572	-.24726	-.52557	-.63079	.35347	
4.	RVG 2501	04.000 S	84.000 E	4860	PG	.89063	-.29106	-.82378	-.16679	.31539	
5.	RVG 2513	01.080 S	85.000 E	4600	PG	.91145	-.32587	-.78788	-.27978	.32595	
6.	RVG 2520	01.125 S	87.020 E	4600	PG	.87957	-.22177	-.78658	-.41872	.19065	
7.	RVG 2528	08.070 S	86.109 E	5200	PG	.89504	-.26691	-.27413	-.82478	.26151	
8.	RVG 2531	07.012 S	88.155 E	5080	PG	.86860	-.26158	-.53161	-.70482	.14417	
9.	RVG 2532	06.001 S	88.090 E	5150	PG	.87537	-.32955	-.36418	-.39331	.69241	
10.	RVG 2533	05.075 S	88.180 E	5030	PG	.83807	-.34545	-.60744	-.43951	.39571	
11.	RVG 2535	03.062 S	88.065 E	4820	PG	.91772	-.38536	-.33708	-.69327	.41794	
12.	RVG 2537	01.059 S	88.095 E	4620	PG	.91334	-.22709	-.73511	-.44973	.25123	
13.	F 47	13.800 S	73.950 E	5190	PG	.93663	-.72173	-.33927	-.47777	.26939	
14.	F 56	14.062 S	73.001 E	4389	PG	.68760	-.61231	-.31733	-.26013	.30014	
15.	F 81	12.490 S	78.011 E	4977	Sp-c	.88063	-.66523	-.23442	-.57234	.25573	
16.	F 99	05.000 S	75.492 E	4492	PG	.79227	-.43174	-.67206	-.20912	.33240	
17.	F 101	07.027 S	78.032 E	5290	PG	.85812	-.74139	-.35002	-.30333	.37970	
18.	F 150	07.644 S	78.954 E	4700	PG	.92240	-.61933	-.41840	-.41431	.44570	
19.	F 151	07.489 S	73.014 E	4750	PG	.90205	-.53312	-.52796	-.48894	.31722	
20.	F 152	07.840 S	77.960 E	NA	PG	.94363	-.52015	-.42385	-.67137	.18589	
21.	F 153	08.024 S	76.967 E	5000	PG	.92272	-.77859	-.20063	-.51487	.10794	
22.	F 154	07.067 S	76.989 E	NA	PG	.92536	-.38898	-.60571	-.20632	.37971	
23.	F 155	07.004 S	78.465 E	NA	PG	.88516	-.61375	-.37346	-.55338	.25053	
24.	F 156	07.067 S	79.500 E	NA	PG	.87597	-.61155	-.26188	-.53825	.36754	
25.	F 157	06.660 S	77.669 E	NA	PG	.91475	-.59119	-.50440	-.45087	.32699	
26.	F 158	06.505 S	78.945 E	NA	PG	.86084	-.48506	-.59523	-.41634	.31100	
27.	F 199	12.337 S	76.377 E	5400	Bgt	.90312	-.53190	-.21855	-.66120	.36753	
28.	F 379	01.089 N	74.670 E	2475	PG	.80524	-.45336	-.38556	-.47925	.46803	
29.	SS 103	11.010 S	74.985 E	5022	Bgt	.93133	-.69447	-.36103	-.48079	.29587	
30.	SS 120	13.006 S	72.984 E	4300	Bgt	.95222	-.69579	-.32206	-.50242	.33458	
31.	SS 121	12.037 S	73.073 E	4430	PG	.91740	-.69414	-.51251	-.37659	.17630	
32.	SS 124	12.017 S	73.000 E	4390	PG	.92241	-.48775	-.38600	-.59912	.42020	
33.	SS 126	14.019 S	72.016 E	4310	Bgt	.92419	-.42492	-.55081	-.21443	.62790	
34.	SS 127	11.999 S	70.990 E	4750	PG	.92951	-.59395	-.50013	-.42112	.38635	
35.	SS 128	11.969 S	75.465 E	5007	Bgt	.94471	-.60484	-.33927	-.60922	.30435	
36.	SS 129	12.006 S	76.452 E	5100	PG	.91840	-.75998	-.37402	-.23737	.38025	
37.	SS 139	11.514 S	81.490 E	5085	PG	.94777	-.70351	-.39004	-.33471	.43436	
38.	SS 183	13.510 S	78.979 E	5388	Bgt	.91224	-.47417	-.37737	-.34235	.65406	
39.	SS 206	15.090 S	83.560 E	NA	PG	.94385	-.54120	-.34848	-.54670	.48025	
40.	SS 210	15.487 S	82.950 E	5040	PG	.75740	-.29804	-.30430	-.23992	.72001	
41.	BB 251	14.890 S	73.530 E	4900	PG	.91914	-.51804	-.36101	-.47454	.54358	
42.	BB 241	13.300 S	72.991 E	4650	PG	.91468	-.60373	-.45363	-.14932	.46877	
							X of Variance	28.09	23.41	21.99	14.86
							Cumulative Variance	28.89	52.89	74.29	89.16

Note : Sampling devices are PG= Petterson grab (optimum vertical penetration depth of 10 cm), Bgt= boomerang grabs attached with 10 cm plastic tube, Sp-c= Spade core to, and V-Gr.= Van Veen Grab to collect the sea floor sediment. Dubious Holocene samples, mainly from larger coring devices having older fauna than *Collosphaera invaginata* zone (NR-1 > 0.17 Ma) of Johnson et al. (1989), were discarded.

of Imbric and Kipp (1992). Details on definitions of the 25 radiolarian groups, the species included, taxonomic references, and may be found in Gupta (1991) and Gupta and Srinivasan (1992), and the same are briefly summarized as followings:

1. *Collosphaera* group : Westberg-Smith *et al.*, 1986; Gupta, 1991, pl. 1, figs. 1-26, pl. 2, figs. 1-3; Gupta and Srinivasan, 1992, pl. 1, figs. 7-13.
2. *Disolenia-Siphonosphaera* group : Gupta, 1991, pl. 2, figs. 4-8, pl. 3, fig. 14. *Disolenia* group Gupta and Srinivasan, 1991, pl. 1, fig. 14.
3. *Acrosphaera* group : Gupta 1991, pl. 2, figs. 9-27; Gupta and Srinivasan, 1992, pl. 1, figs. 1-6.
4. *Actinomma* group : Westberg Smith *et al.*, 1986, p. 772. *Actinomma* group Gupta 1991, pl. 4, figs. 4-13, pl. 5, figs. 1-8, pl. 6, fig. 4-6; Gupta and Srinivasan, 1992, pl. 1, figs. 35-37.
5. *Spongodiscids* group : Westberg-Smith *et al.*, 1986, p. 772; *Spongopyle* group Mullineaux and Westberg-Smith, 1986, p. 66, pl. 1, figs. 7a,b; Gupta, 1991, pl. 8, fig. 21, pl. 9, figs. 8-22, pl. 10, fig. 1.
6. *Spongaster-Spongocore* group : Mullineaux and Westberg-Smith, 1986, p. 66, pl. 1, fig. 13; Gupta, 1991, pl. 9, figs. 23-24, pl. 10, figs. 2-4.
7. *Halionna Ektomma* group : Gupta 1991, pl. 5, figs. 20-21, pl. 6, 1-2, 4-6.
8. *Hexacantium* group : Riedel *et al.*, 1985, pl. 1, figs. 6a-c, 7a-c; Westberg-Smith *et al.*, 1986, p. 771; Gupta, 1991, pl. 6, figs. 11-21; Gupta and Srinivasan, 1992, pl. 2, figs. 1-4.
9. *Echtroniids* group : *Hymenocentrum* group Riedel *et al.*, 1985, p. 505, pl. 2, figs. 2a, b; *Echtroniids* group Gupta, 1991, pl. 8, figs. 9-12; Gupta and Srinivasan, 1992, pl. 1, figs. 15-18.
10. *Stylodictya-Stylochlamydidium* group : *Stylodictya* group Westberg-Smith *et al.*, 1986, p. 772. *Stylodictya-Stylochlamydidium* group Gupta, 1991, pl. 9, figs. 1-7; Gupta and Srinivasan, 1992, pl. 1, figs. 19-24.
11. *Artiscins (Didymocyrtis)* group : Mullineaux and Westberg-Smith, 1986, p. 64, pl. 2, fig. 1. *Didymocyrtis* group Gupta, 1991, pl. 8, figs. 3-8.
12. *Phacodiscids (Heliodiscus)* group : Westberg-Smith *et al.*, 1986, p. 772. *Heliodiscus* group Gupta, 1991, pl. 10, figs. 5-13; Gupta and Srinivasan, 1992, pl. 2, figs. 7,8.
13. *Litheliids* group : Mullineaux and Westberg-Smith, 1988, p. 66, pl. 2, figs. 1a, b. *Litheliids* group Gupta 1991, pl. 11, figs. 1-8; Gupta and Srinivasan, 1992, pl. 2, figs. 20-21.
14. *Pyloniids* group : Mullineaux and Westberg-Smith, 1986, p. 66, pl. 2, fig. 2; Gupta, 1991, pl. 10, figs. 15-21; Gupta and Srinivasan, 1992, pl. 2, figs. 15-16.
15. *Larospira quadrangula* group : Mullineaux and Westberg-Smith, 1986, p. 66, pl. 2, fig. 7; Gupta, 1991, pl. 11, figs. 9-11; Gupta and Srinivasan, 1992, pl. 2, figs. 17-18.
16. *Stylosphaera* group : Westberg-Smith *et al.*, 1986, p. 772; Gupta, 1991, pl. 7, figs. 10-21 and 23-26; Gupta and Srinivasan, 1992, pl. 1, figs. 38-42.
17. *Lophophaena* group : Mullineaux and Westberg-Smith, 1986, p. 67, pl. 2, figs. 13 a-c. *Lophophaenus* group Gupta, 1991, pl. 12, figs. 6-13; Gupta and

- Srinivasan, 1992, pl. 2, figs. 28-31.
18. *Phormospyris Lophosyrts* group : Gupta, 1991, pl. 12, figs. 24-26, pl. 13, figs. 1-9. *Phormospyris* group Gupta and Srinivasan, 1992, pl. 2 figs. 23-25.
  19. *Sethophormin* group A,B. : Riedel *et al.*, 1985, p. 508, pl. 4, figs. 2a, b; Mullineaux and Westberg-Smith, 1986, p. 67, fig. 17; Gupta, 1991, pl. 13, figs. 17-20.
  20. *Petrocanium* group : Mullineaux and Westberg-Smith, 1986, p. 67, pl. 3, figs. 6 a-c; Gupta, 1991, pl. 14, figs. 15-21; Gupta and Srinivasan, 1992, pl. 3, figs. 12-14.
  21. *Eucyrtidium* group : Mullineaux and Westberg-Smith *et al.*, 1986, p. 67, pl. 3, fig. 4; Gupta, 1991, pl. 16, figs. 8-25; Gupta, and Srinivasan, 1992, pl. 3, figs. 8-11.
  22. *Theocorythium* group : Westberg-Smith *et al.*, 1986, p. 775; Gupta, 1991, pl. 15, figs. 13-16.
  23. *Anthoeyrtidium* group : Mullineaux and Westberg-Smith, 1986, pl. 3, figs. 11 a, b; Gupta, 1991, pl. 16, figs. 26-31; Gupta and Srinivasan, 1992, pl. 3, figs. 26-28, and 52.
  24. *Lamprocyclus* group : Mullineaux and Westberg-Smith, 1986, pl. 3, figs. 13 a, b; Gupta, 1991, pl. 17, figs. 29-38, pl. 18, figs. 1-5; Gupta and Srinivasan, 1992, pl. 3, fig. 29.
  25. *Phormostichoartus* group : Mullineaux and Westberg-Smith, 1986, pl. 3, figs. 14a, b; Gupta, 1991, pl. 18, figs. 20-22; Gupta and Srinivasan, 1992, pl. 3, figs. 36-42.

### Data Sets and Analysis

Computer programming of the sequential procedures to execute Q-mode factor analysis, linear and curvilinear multiple regression analyses by least square technique to derive transfer functions, and their use in paleoestimates as described by Imbrie and Kipp (1971) was performed and tested on their data-set for reproducibility (Fernandes and Gupta, 1994). Success of the programming resulted in achieving similar results presented in different tables in Imbrie and Kipp (1971). We related our paleontological data with surface salinity, SST data of Wyrтки (1971) and (Levitus (1982); and ppp data of Krey and Babenard (1976). The interpolation of contour values of oceanographic variables (Figs. 1a-d) digitization of data at respective sampling locations was performed to relate factor values in regression analysis step. National Oceanic and Atmospheric Administration (NOAA) data (Levits, 1982) of SST and salinity for Spring (May-June-July) and Fall (Nov. Dec-Jan) seasons corresponding to southwest and northeast monsoon was acquired and interpolated at sampling locations from digital tapes on  $1^{\circ} \times 1^{\circ}$  square grid. Both the data-sets produced transfer functions with almost similar statistics. Derived transfer functions were used to estimate changes in the late Miocene Sawai Bay Formation.

### Results and Discussion

#### Q-mode Factor Analysis

Surface sediment data (42 samples, 25 groups) was normalized within each sample to give each sample equal weight and subjected to Q-mode factor analysis that



Table 2. Supra-generic groups, their percentage ranges used in analyses and Factor Score Matrix after varimax rotation.

Supra-generic groups	% range in calibration	Factors (Assemblages)			
		SW (F1)	NE (F2)	Transitional (F3)	Southern (F4)
1. Collosphaera	9.57	-.27212	-.09077	-.33915	-.29170
2. Disolenia-Siphonos.	6.05	-.15192	.10592	-.51068	-.15314
3. Acrosphaera	4.49	-.37855	-.04452	-.19013	-.16683
4. Actinomma	5.52	-.10767	-.14761	-.02574	-.13577
5. Spongodiscids	31.59	.09932	-.43396	.01762	-.03441
6. Spongaster	6.56	-.01192	-.49831	.04614	-.08668
7. Halionna/Elatonma	5.41	-.26588	-.35968	.21388	-.00975
8. Hexacantium	8.40	-.34306	-.18805	.26151	.01958
9. Euchitoniids	21.07	.06300	-.20593	-.29991	-.06501
10. Stylocicya/chlamydia	13.79	.15791	-.37434	-.23107	.21006
11. Didymocyrtis/Artiscin	19.52	-.42706	.10249	.07717	.31753
12. Helioliscus	4.87	-.12165	-.15913	.00675	-.02425
13. Litheliids	6.45	-.27713	-.09160	.00033	-.02971
14. Pyloniids	24.60	-.37686	.09540	.02228	.22342
15. Larconpira	12.33	-.20666	.03964	.04093	.07355
16. Stylosphaera	4.79	.16832	-.28923	.01770	.28804
17. Lophosphaeniids	3.30	-.03439	.07242	-.29431	.09401
18. Phorocypria-Lophou.	6.76	-.08553	-.14793	-.21553	.33033
19. Sethophorians	5.20	-.07316	.08825	-.08359	.04617
20. Pterocanium	6.16	.01225	-.02954	-.16960	.26739
21. Eucyrtidium	2.50	.01047	-.01623	-.31270	.08333
22. Theocorythium	4.48	-.00515	.01730	-.09001	.25170
23. Anthocyrtidium	6.83	-.09797	.05598	-.04564	.34600
24. Lamprocyclas/cyrtis	6.16	.05572	.03603	.01976	.39794
25. Phormostichoartus	3.29	.10506	.00582	-.21500	.07059

resolved four varimax factors accounting for 89.15% of distributional variance of the groups. The variance, cumulative variance of each factor and communality are also presented in Table 1. The varimax factor score matrix (F<sup>1</sup>) of each of 25 groups shows the relative importance of each group in each factor (Table 2). These factors are named after dominant groups and the geographical area of higher loading. The cumulative variance in our 4-factor model is ecologically significant as it represents 89.15% of total variance. Communality of samples ranged from 0.688-0.952 accounting for 82.93-97.58% of the informations retained. Communality for each samples is

a useful internal check of distortion of surface-sediment data due to differential dissolution, stratigraphic mixing, taxonomic inadequacies (by lumping several species into broadly defined group) and local ecological anomalies in factor-assemblage model (Imbrie *et al.*, 1973). Higher communality ( $h^2 = 0.8915$ ) for broadly-defined radiolarian groups shows that the abundances of groups have not been distorted. It shows that lumping of several species into a broadly-defined group based on few persistent common characters since late Neogene has successfully retained the environmental informations (89.42%) preserved in surface sediments and describe major feat-

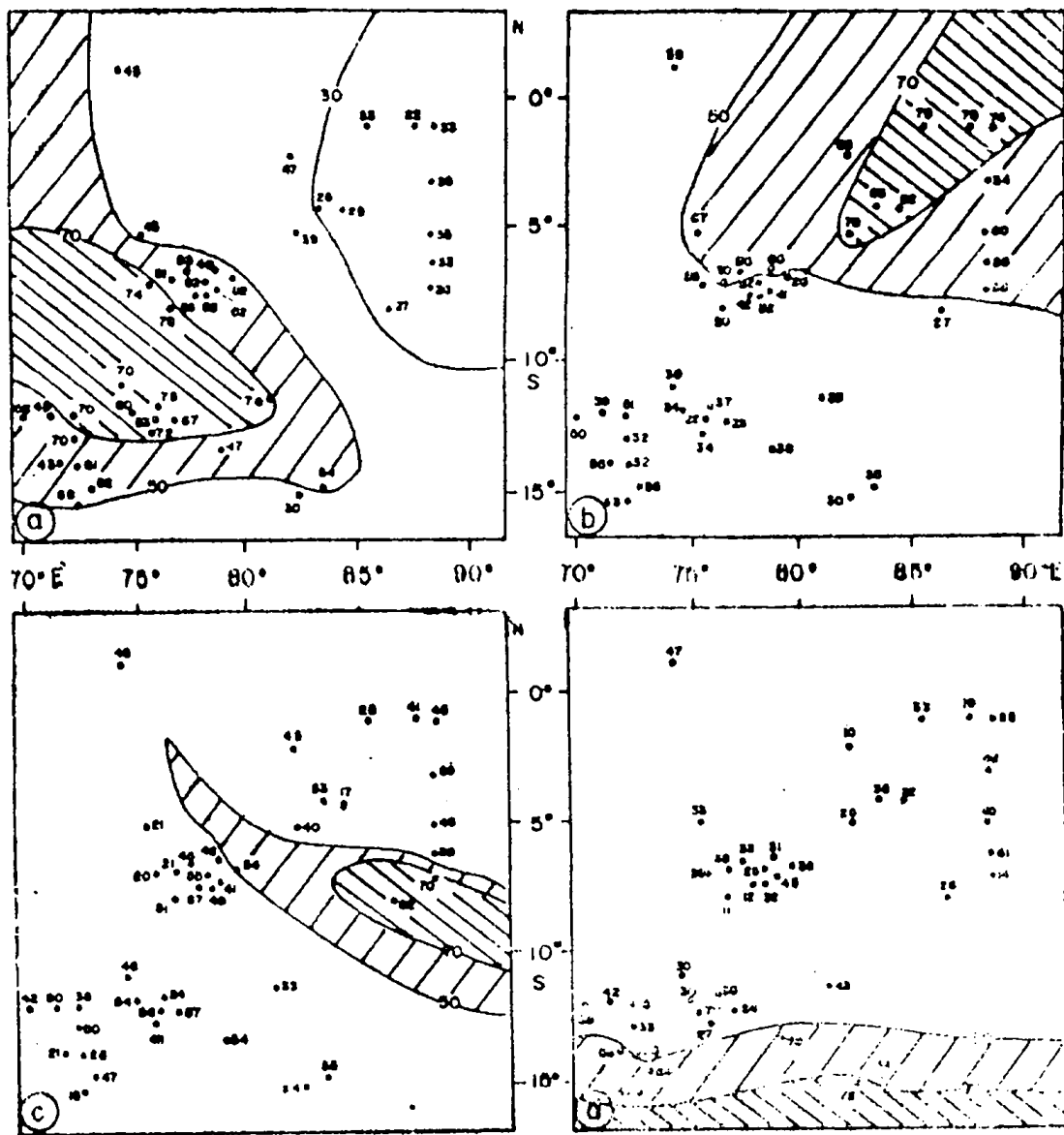


Fig. 3. Factor loading maps and areas of dominances shown by diagonal lines. (a) southwest hypersaline factor 1; (b) northeast hyposaline factor 2; (c) oblique-transitional factor 3; and (d) southern hydrographic front at 10-12°S factor 4 in the central Indian Basin.

ures of the radiolarian distribution in the basin.

#### Factor Mapping

The factor loading values of each factor

(Table 1) were plotted at respective sampling sites on geographical maps (Fig. 3a-d) to examine their spatial distribution and to relate them with oceanographic characteristics of the overlying surface water in the

basin.

*Factor 1 (F1), Southwest Artiscin-Pyloniid-Acrospira assemblages*

The first factor accounted for 28.88% of variance with highest loading in the southwestern area (Fig. 3a). It is dominated by Artiscins (*Didymocystis tetrathalmus*), Pyloniids (*Tetrapyle octacantha*, *Octopyle stenozona*, and *Hexapyle dodecanthal*) and *Acrospira* groups. Our decision to count all Pyloniids together is supported by Nigrini's (1991, p. 94) expression for the need of % data on combined group of *T. octacantha* and *O. stenozona* to establish its increased abundance in area of monsoonal upwelling. This factor is comparable to Moore's (1978) Pan-Pacific western tropical factor dominated by *D. tetrathalmus* as the dominant species are similar in all. The SST is comparatively lower (23-27°C), whereas surface salinity (34.5-34.9 ppt) of the surface water in this area is higher during SW than NE monsoon (Fig. 1). This factor is correlated with cooler (23-27°C) and hypersaline (>4.5ppt) and highly productive (>0.3 mg C/m<sup>3</sup>/d) surface water mass during SW monsoon. Unfortunately, no radiolarian plankton-tow data at various waters depths is available from the tropical Indian Ocean. But their representatives of Pyloniids group *T. octacantha* and *O. stenozona* have abundance maxima at 50 m of the water depth in the northwest Pacific Ocean (Kling, 1979). Dwoletzky and Morley (1987) reported highest number of *T. octacantha* and *Hexapyle* spp. and *D. tetrathalmus* from 20-50 m water depths near chlorophyll-a maximum at MOCN 016-017 plankton tow sites in the eastern equatorial Atlantic Ocean. *Acrospira* group is a known colonial radiolaria

dwelling in surface water. We assumed that the habitat of Artiscins and Pyloniids is similar to that of Pacific and Atlantic Oceans and represents surface water characteristics in tropical Indian Ocean also.

*Factor 2 (F2), Northeast Spongaster-Spongodiscids-Stylodictya assemblages*

The second factor accounted for 23.41% of variance with highest loading in the northeastern area, north of 6°S (Fig. 3b). It is dominated by Spongaster, Spongodiscids and *Stylodictya/Stylochlamydidium* groups. Constituent species of these groups are *Spongaster tetras*, *S. tetras irregularis*, *Spongocore puella*, *Spongotrochus glacialis*, *Spongodiscus resurgens*, *Spongodiscus bicavatus*, *Spongurus* spp., *Spongopyle osculosa*, *Stylochlamydidium asteriscus*, *S. venustum*, and *Stylodictya validispina*. Lozano and Hays (1976) also combined the abundances of *S. glacialis* and *S. osculosa* in their transfer function. This factor is comparable to Moore's (1978, fig. 11a) New Guinea factor dominated by *Stylochlamydidium asteriscus* in western tropical Pacific, a region that also receives fresh water flux from the south China-Sea during southwest monsoon. Dwoletzky and Morley (1987) reported highest number of *S. tetras*, *Spongodiscus* spp. and *S. glacialis* at 20-40 m water depths coinciding with chlorophyll-a maximum at MOCN-016-017 plankton tow sites in the eastern equatorial Atlantic Ocean which shows that the group represents surface-water characters. Higher SST (>27-28°C) north of 6°S and lower salinity (34.5ppt) and low ppp (<0.2 mg C/m<sup>3</sup>/d) in the NE area during SW monsoon is evident (Fig. 1). Therefore, this factor is related to higher SST (>27-28°C), lower salinity (<34.5ppt)

and low ppp (0.05-0.1 mgC/m<sup>3</sup>/d) during-SW monsoon.

#### *Factor 3 (F3), transitional assemblage*

The third factor accounted for 21.98% of variance with highest loading in the area shown by diagonal lines (Fig. 3c). It is dominated by *Disolenia*, *Collosphaera*, *Eucyrtidium* and *Euchitoniids* groups. *Euchitoniid* group is comprised of *Euchitonia elegans*, *E. furcata*, *Euchitonia sp.*, *Dictyocoryne truncata*, *Dictyocoryne profunda*, and *Hymeniastrum euclidis*. Morley (1989, p. 296) also counted *E. furcata* and *E. elegans* together as *Euchitonia spp.* This factor is comparable to western Pacific factor dominated by *E. furcata*, *E. elegans*, *D. profunda* and *D. truncata* representing warmer waters of western Pacific tropical gyre (Moore, 1978, fig. 9a). *Disolenia*, *Collosphaera*, *D. truncata* and *Euchitonia spp.* live 10-40 m water depth at 23-40 m water depth coinciding with chlorophyll-a maximum at MOCN-016-017 plankton tow sites in the eastern equatorial Atlantic Ocean (Dworetzky and Morley, 1937). The transitional assemblage seems to be an oblique boundary of salinity contrast along 34.5 ppt isohaline (Fig. 1d) between SW and NE assemblages.

#### *Factor 4 : Southern 10-12°S hydrographic front assemblage*

The fourth factor accounted for 14.86% variance with higher loading in southern part of the basin south of 12°S latitude (Fig. 3d). It is dominated by *Lamprocyclas*, *Anthocyrtidium* and *Lophospyris-Phormospyris* groups. The area of dominance of 4th factor is south of 10-12°S hydrographic front of Wyrтки (1973) in the equatorial Indian Ocean.

#### **Regression Analysis**

The factor loading values in each 42

surface sediments were related to modern SST, salinity and PPP of the surface water overlying each sampling site during SW and NE monsoons using multiple regression by least square technique. Both linear and curvilinear equations were derived and examined. Results of curvilinear equations have better statistics and lower residuals (observed minus estimated). Therefore, these equations are used in paleoestimates. The regression coefficients of the variables, the intercepts for curvilinear equation, proportion of variance, multiple correlation coefficients (r), standard errors of estimate (s.e.e), and % of range of variables expressed by s.e.e. of SST, salinity, PPP during SW monsoon are listed in the summary statistics (Table 4). It is evident that the equations for the southwest monsoon are significant at 0.001 level (99.9%) for the salinity-July August, salinity - spring, PPP-SWM, SST-Spring and SST-August. The regression, the intercepts and factor score (F') matrix define the transfer functions derived from the faunal and SST, salinity and PPP data-sets. The equations are named as NORTHEASTERN INDIAN OCEAN (NIO) after Gupta and Fernandes (GF) with suffix of the numerals (Table 3).

#### *Constraints on the tropical transfer function*

We achieved low standard errors of estimate for SST-August and SST-Spring which shows that our estimates are accurate within + or - 1°C. Unlike higher latitude regions, the faunal factors in tropics (Atlantic) are not strongly correlated due to lower SST-range (24-29°C), but they show good correlation (r=0.6) (Ravelo *et al.*, 1990; Gupta in press). Moreover, the Pacific and Atlantic Oceans do not have much influence of monsoon compared to northern

Table 3. Curvilinear equations and summary statistics for various variables.

Data Source	<----- Myrtek (1971)----->			<----- Levitus (1982)----->		<Krey & Baben., 76>
Variables->	SST-August	-----Salinity-----		Salinity	SST-Spring	PPP-SUM
Equation No.	NIO-GF-1	July-August	Nov.-Dec.	Spring	NIO-GF-5	NIO-GF-6
<b>14 Terms</b>						
F1	-65.87894	+11.63134	+2.97422	+7.78309	-171.86481	+ 62446
F2	-67.26555	+13.12113	-11.46072	+6.07707	-173.30021	+4.19586
F3	-65.77937	+14.50109	-4.36903	+8.27528	-155.10130	+1.69468
F4	+61.94474	-12.77112	-6.01031	-7.19667	+157.10580	-1.13188
F1 <sup>2</sup>	-21.09511	+1.17110	-1.37387	+2.04791	-50.57022	54321
F1:F2	-37.92229	+8.05157	-7.27118	+3.11739	-101.12930	+1.83991
F1:F3	-41.49414	+7.64118	+1.05186	+4.55957	-100.50540	+1.46463
F1:F4	+47.19274	-9.15100	-5.34537	-4.00151	+106.95960	-1.73159
F2 <sup>2</sup>	-22.54539	+2.83138	-11.63023	+1.36714	-53.97767	+2.24074
F2:F3	-39.96597	+7.81106	-8.56556	+4.68777	-98.40904	+1.97749
F2:F4	+36.25882	-7.18106	-1.19216	-2.55199	+90.48481	-1.84159
F3 <sup>2</sup>	-24.11968	+4.15172	-4.30835	+1.82796	-53.08044	+ 63055
F3x74	+26.11875	-5.98103	+7.3619	-5.79482	+73.32769	+76531
F4 <sup>2</sup>	-22.22023	+3.14101	+1.29581	+2.30823	-51.35821	+ 07476
Intercept	-25.36438	46.01700	35.31356	41.00345	-114.068	1.68858
X Variance	53.588	80.265	67.005	55334	6593	74.688
Adjusted Cor. Coefficient	r=0.543	0.837	0.706	0.56722	0.6947	0.785
S.d. Err. Est. (S.E.E.)	0.9°C	0.12ppt	0.2ppt	0.143ppt	1.026°C	0.09 mgC/m <sup>2</sup> /d
Range calibrated	20.6-25.3	34.8-34.1	35.1-33.8	34.76-34.11	29.74-24.46	0.55-0.10
Expressed in S.E.	3.3°C	0.7ppt	1.3ppt	0.65ppt	5.283°C	0.45 mgC/m <sup>2</sup> /d
X Expressed in S.E.	27.3	17.15	15.30	22.02	18.93	20.00

Note: @ = Adjusted for degree of freedom (N-2). Multiple correlation coefficients higher than threshold of  $r=0.439$  for  $N=40$  at 0.201 level of significance is considered to be trustworthy (cf. Imbrie & Kipp, 1971, p. 106) at significance level of 0.001 (99.9%). Our MCC > 0.534-0.837 show massive significance levels at .001 and 99.9% correlation with SST-Aug., salinity-July-August, SST-Spring and salinity-Spring during SW monsoon in the central part of the tropical Indian Ocean. Our MCC range ( $r=0.5-0.8$ ) is close to the CLINAPS's MCC range ( $r=0.6-0.9$ ) used for the Pacific SST reconstruction (Moore, et al. 1980, cf. p. 221)

Indian Ocean, which is land locked in the north by the Asian plate and restricts the mixing of north pole water to produce similar thermal gradient. Therefore, the order of the faunal sensitivity to SST ( $r=0.9$ ) and salinity ( $r=0.8$ ) in the Atlantic and Pacific Oceans (Imbrie and Kipp, 1971; Moore, 1973b) is reversed in northern Indian Ocean, i.e., salinity-July-August ( $=0.837$ ) and SST-

Spring ( $r=0.695$ ) because of extreme salinity changes due to monsoon. Furthermore, Moore *et al.* (1980, cf. p. 221) used DP-1 transfer function with multiple correlation coefficient as low as  $r=0.62$  in paleoestimates of the eastern equatorial Pacific. Imbrie and Kipp (1971, cf. p. 106) used data from the entire Atlantic Ocean and mentioned that any correlation coefficient ( $r$ ) higher

than the threshold value of significance level at 0.001 level (0.411 for their  $N=61$ ; whereas, it is 0.499 for our  $N=42$ ) is statistically significant and transfer function is valid to estimate changes at 99.9% confidence level. Comparing the smaller geographic area of the central Indian Basin ( $20^{\circ}\times 16^{\circ}$ ) to the entire Atlantic and Pacific Oceans, our correlation coefficients (m.c.c. range  $r=0.543-0.837$ ) are significant for the reliable estimates of the SST-August, SST-Spring, salinity-July-August, salinity-spring and PPP-SWM (Table 3), and are at par with the CLIMAP's standard for SST reconstruction in the Pacific Ocean at 18,000 years (m.c.c. range  $r=0.6-0.9$ , Moore *et al.*, 1980).

#### Reliability of transfer functions

Using the ecological equations in Table 3, we estimated oceanic variables for the 42 surface sediments (Table 4) that are sound within the  $\pm$  or  $-$  limits of the standard errors of estimates. The estimated values are subtracted from the observed values at each of 42 sampling sites for residuals of each variable. The spatial distributions of residuals  $> 1.0$  s.e. of these variables have no geographic trend. The soundness of estimated values of these variables is depicted in X-Y graphs, which shows almost linear relationship for the majority of estimates within the coherent bands of respective standard errors of estimates (Fig. 4). Therefore, it has similar potential for longer geological time scale such as late Miocene as the species or species group data had for the late one million years.

#### Paleoestimates

Paleoestimates from the late Miocene radiolarian data of Sawai Bay Formation,

Neill Island (Gupta and Srinivasan, 1992) are presented in Table 5. Paleoestimates show warmer periods associated with lower salinity due to higher fresh water influx alternating with colder periods with higher salinity due to poor fresh influx from the Ganges-Brahmaputra rivers into the Bay of Bengal (Fig. 5). Gupta and Srinivasan (1992) recognized warmer-humid and colder-arid periods during *Stichocorys peregrina*, *Didymocyrtis antepenultima* and *Didymocyrtis penultima* zones respectively, and attributed warmer climatic periods (W) corresponding to W-11 (5.6-5.0 Ma) and W-9 (8.2-7.9 Ma) warmer events of Barron and Keller (1983) in Sawai Bay Formation (Fig. 5). Besides confirming W-11 and W-9, it also has resolved W-10 (6.5-6.1 Ma) and W-8 (9.2-9.0 Ma) warmer periods. SST-August fluctuated within  $1.3^{\circ}\text{C}$  in late Miocene that concurs with CLIMAP (1981), Prell *et al.* (1980, cf. figs. 9a-b) and COHMAP (1988) that region around Andamans in the Bay of Bengal witnessed little ( $\sim 1^{\circ}\text{C}$ ) change in SST-Aug. during colder periods such as last glacial maxima (LGM). Similarly, SST spring (May-June-July) fluctuated within  $3^{\circ}\text{C}$  around the Andamans during late Miocene.

Salinity-July-Aug. fluctuated within 0.4 ppt in Sawai Bay Formation. Association of SST-peaks with salinity-troughs and vice versa is in agreement with Prell *et al.* (1980) that salinity was higher in the Bay of Bengal during weaker southwest monsoons in colder periods like LGM than at present. Salinity at  $13^{\circ}\text{N}$  latitude, north of Neill Island ( $12^{\circ}\text{N}$ ), was higher ( $> 35$  ppt) during LGM than at present ( $\sim 32$  ppt) suggesting considerably low fresh water runoff into the Bay of Bengal in colder periods analogous to

Table 4. Observed (Ob.) and estimated (Est.) values of dependent variables (Y) using the curvilinear equations.

S.N.	SST-Aug. $^{\circ}\text{C}$		SST-Spring $^{\circ}\text{C}$		Salinity J-Aug.		Salinity N-Dec.		Salinity-spring		PPP-SVM	
	Ob.	Est.	Ob.	Est.	Ob.	Est.	Ob.	Est.	Ob.	Est.	Ob.	Est.
1.	28.60	28.029	28.899	29.060	34.400	34.457	34.600	34.556	34.560	34.478	0.300	0.373
2.	28.30	28.116	29.209	28.620	34.200	34.313	34.300	34.147	34.460	34.444	0.400	0.368
3.	28.30	28.434	29.744	28.650	34.200	34.025	34.200	34.201	34.510	34.481	0.250	0.141
4.	28.30	28.057	28.401	28.660	34.200	34.299	34.100	34.214	34.510	34.529	0.250	0.263
5.	28.60	28.195	29.221	29.090	34.200	34.211	34.100	33.956	34.560	34.455	0.300	0.347
6.	28.30	28.355	29.067	29.130	34.200	34.039	33.800	33.932	34.530	34.617	0.300	0.189
7.	27.30	27.521	27.856	27.680	34.200	34.196	34.600	34.554	34.210	34.229	0.250	0.223
8.	27.60	27.564	28.064	28.380	34.100	34.212	34.600	34.560	34.360	34.373	0.150	0.240
9.	27.60	27.270	27.469	28.670	34.100	34.324	34.500	34.547	34.420	34.606	0.150	0.190
10.	27.60	28.078	29.153	28.890	34.100	34.291	34.500	34.407	34.470	34.466	0.150	0.296
11.	28.30	27.401	28.395	29.150	34.200	34.356	33.900	34.340	34.530	34.408	0.200	0.268
12.	27.00	28.107	29.245	29.150	34.200	34.181	33.800	33.811	34.490	34.471	0.300	0.342
13.	25.60	26.502	27.578	26.380	34.500	34.630	34.700	34.639	34.280	34.211	0.500	0.501
14.	25.30	26.745	26.500	25.650	34.200	34.862	34.800	34.922	34.370	34.409	0.500	0.469
15.	26.30	26.773	27.849	26.940	34.700	34.657	34.700	34.693	34.180	34.150	0.500	0.519
16.	28.00	27.967	28.541	28.590	34.600	34.539	35.000	34.811	34.350	34.435	0.400	0.358
17.	28.00	26.308	25.917	26.420	34.600	34.679	34.600	34.615	34.170	34.263	0.500	0.496
18.	27.30	25.907	26.174	29.140	34.600	34.735	34.400	34.681	34.230	34.364	0.500	0.504
19.	27.60	26.902	27.564	28.200	34.600	34.602	34.600	34.483	34.200	34.352	0.500	0.466
20.	27.30	26.728	27.581	28.260	34.600	34.611	34.600	34.561	34.150	34.212	0.500	0.481
21.	27.60	26.745	27.597	28.290	34.600	34.582	34.600	34.572	34.110	34.081	0.500	0.516
22.	27.30	26.778	27.384	28.410	34.600	34.614	34.400	34.609	34.170	34.271	0.500	0.513
23.	27.30	26.932	27.981	28.300	34.600	34.644	34.400	34.761	34.230	34.239	0.500	0.477
24.	27.30	26.596	27.555	28.160	34.600	34.668	34.300	34.633	34.280	34.277	0.500	0.484
25.	27.60	26.637	27.221	23.460	34.600	34.653	34.500	34.563	34.220	34.338	0.500	0.492
26.	27.60	27.562	28.456	28.340	34.600	34.507	34.300	34.506	34.290	34.381	0.500	0.427
27.	28.00	26.788	27.759	27.350	34.700	34.593	34.700	34.486	34.140	34.263	0.500	0.442
28.	28.60	27.414	28.246	29.100	34.700	34.532	35.100	34.778	34.750	34.459	0.250	0.344
29.	26.30	26.416	27.339	27.760	34.700	34.661	34.700	34.653	34.150	34.244	0.500	0.503
30.	25.60	26.038	26.809	26.240	34.700	34.693	34.700	34.586	34.340	34.257	0.500	0.517
31.	25.60	27.509	28.720	26.790	34.700	34.521	34.700	34.656	34.320	34.263	0.500	0.434
32.	26.00	26.586	27.128	26.790	34.700	34.593	34.700	34.472	34.320	34.416	0.500	0.395
33.	25.30	26.149	26.040	25.240	34.700	34.604	34.700	34.771	34.440	34.378	0.500	0.447
34.	26.00	26.230	26.511	26.290	34.700	34.694	34.700	34.565	34.480	34.361	0.500	0.508
35.	26.00	26.309	27.073	27.450	34.700	34.688	34.700	34.577	34.150	34.259	0.500	0.494
36.	25.60	26.164	26.978	27.330	34.700	34.626	34.700	34.597	34.140	34.233	0.500	0.504
37.	26.30	25.631	25.998	25.980	34.600	34.723	34.600	34.658	34.420	34.296	0.500	0.535
38.	25.60	25.896	25.756	25.560	34.700	34.649	34.600	34.697	34.390	34.493	0.500	0.407
39.	25.30	25.964	26.164	24.630	34.700	34.690	34.600	34.514	34.760	34.443	0.250	0.433
40.	26.60	26.352	24.461	24.310	34.700	34.642	34.600	34.568	34.760	34.689	0.250	0.264
41.	25.50	26.067	26.223	25.360	34.800	34.665	34.800	34.599	34.370	34.476	0.500	0.414
42.	25.30	25.779	26.069	24.700	34.800	34.736	34.900	34.748	34.430	34.238	0.500	0.545

LGM (Cullen, 1981). Similarly, spring-salinity estimates fluctuated within 0.35ppt around Andamans. Lowering trend in the spring salinity suggests strengthening of monsoon since 9.0-5.0 Ma. The modern mean salinity (July-Aug.) is  $\sim 33.5$ ppt, whereas it was 34 ppt around the Neill Island in the late Miocene (Fig. 6). The hypersal-

ine water mass was flushed out of the Bay of Bengal by the hyposaline water due to riverine fresh water flux from the Ganges-Brahmaputra rivers during periods analogous to the Holocene and the reverse happened in colder periods analogous to LGM. Oscillation of hypersaline water mass in the Bay of Bengal suggests monsoonal fresh water

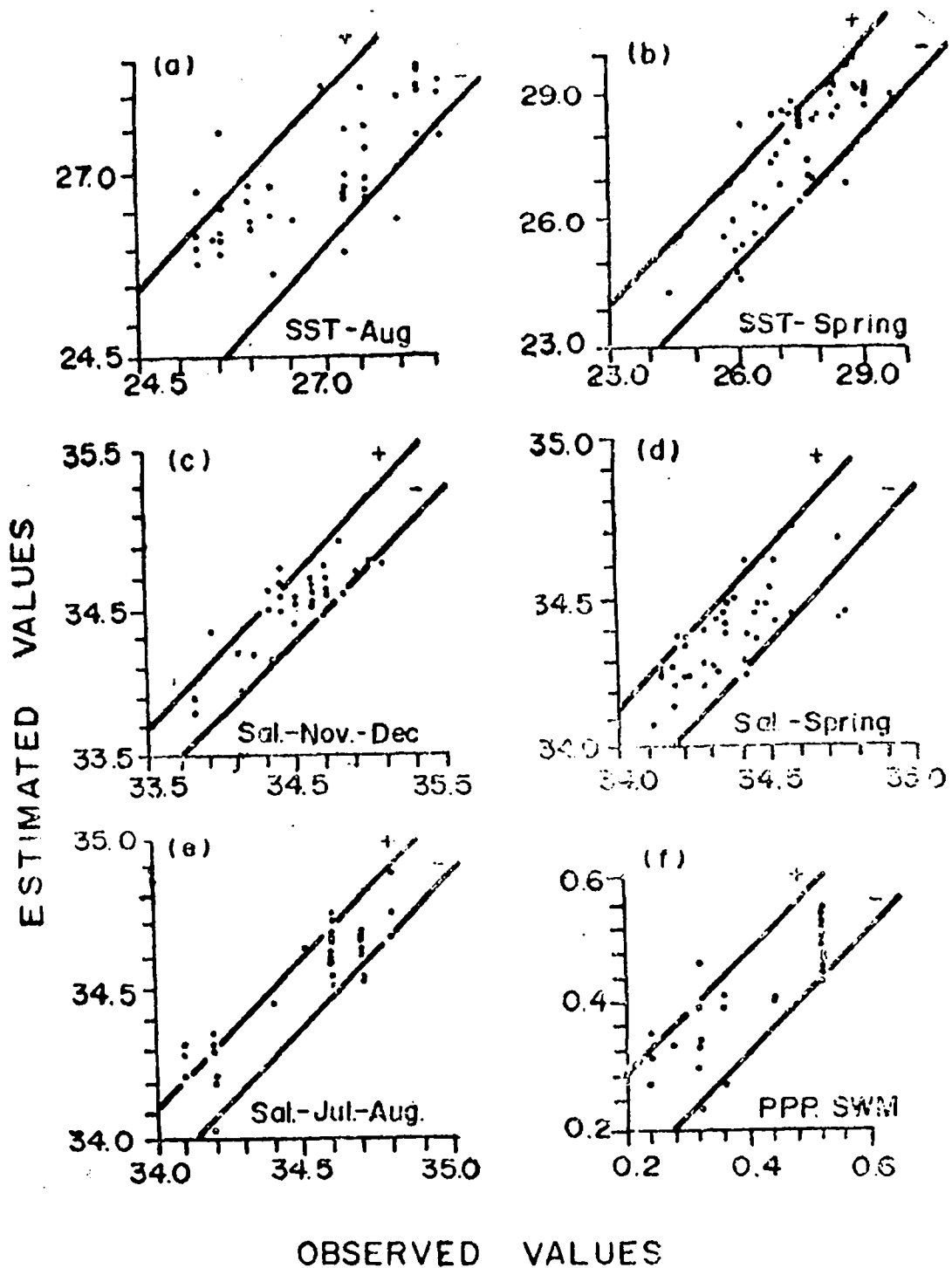


Fig. 4. X-Y graphs depicting linear relationship between observed and estimated values within a confidence band (+ or -) of the standard errors of estimate of the SST-Aug. (a), SST-Spring (b), salinity-Nov-Dec. (c), salinity-Spring (d), salinity-July-Aug. (e) and PPP-SWM monsoon index (f). It suggests that estimates from the transfer functions are reliably reproducible.



Table 5. Paleostimates in Savai Bay Formation, Neill Island, Andamans.

S.N. Sample number	Factor 1	Factor 2	Factor 3	Factor 4	Salinity			SST		PPP-SUM
					Nov.-Dec.	July-Aug.	Spring	August	Spring	
1. Mf538	-.28736	-.45028	-.55496	.30356	35.075	34.347	34.347	28.401	28.483	0.175
2. Mf536	-.31057	-.36581	-.54970	.33465	35.171	34.466	34.466	28.193	28.424	0.204
3. Mf533	-.38501	-.34016	-.48493	.24400	35.549	34.851	34.851	27.331	27.599	0.312
4. Mf530	-.35676	-.35141	-.64343	.16222	35.408	34.648	34.648	27.278	27.995	0.323
5. Mf527	-.40670	-.47352	-.43260	.16011	35.635	34.803	34.803	27.616	27.536	0.280
6. Mf523	-.41280	-.32549	-.48260	.33791	35.216	34.678	34.678	27.801	28.178	0.321
7. Mf520	-.19319	-.45944	-.47389	.33393	35.372	34.420	34.420	28.087	27.882	0.049
8. Mf516	-.25376	-.48767	-.44547	.32207	35.338	34.456	34.466	28.244	28.025	0.127
9. Mf511	-.19350	-.57538	-.40555	.27174	35.393	34.462	34.462	27.914	27.498	0.055
10. Mf507	-.27600	-.49676	-.45841	.35386	35.116	34.359	34.359	28.527	28.360	0.151

flux related salinity changes in the north-eastern Indian ocean.

### Implication on Paleomonsoonal Studies

Probably, Gupta *et al.* (1988) were first to present a paleomonsoonal scenario with enhanced riverine sedimentary discharge from the Irrawadi river during warmer periods is one of the cause of basinal shallowing of Savai Bay Formation in the late Miocene (~9.0-5.0 Ma). Several results converging to the late Miocene origin of monsoon have appeared in subsequent years. Quade *et al.* (1989) reported the onset of an intensified monsoon at ~7.4-7.0 Ma that reflected in C<sub>2</sub> and C<sub>1</sub> carbon-isotopic shift in soil profiles and vegetational changes from Potwar Plateau, Pakistan. Burrelle (1989) suggested the initiation of monsoonal circulation in northern Indian Ocean at ~10 Ma that resulted in a remarkable increase in diatom abundance. Nigrini (1991) found late Miocene (~8.5 Ma) paleomonsoonal signals related to endemic monsoonal upwelling fauna at ODP-117-122 site. Rapid build-up of the Bengal and Indus fan sediments in the late Miocene

indicates elevation changes in the Himalaya and is considered to be associated with onset of monsoon (Cochran, 1990; Rea, 1992). Klootwijk *et al.* (1992) reported distinct climatic changes at 10.4-10, 8.8, 6.5, 5.4-5.1, 2.7-2.5, 1.9 and 1.2-1.1 Ma related to sedimentary flux from the Ganges-Brahmaputra drainage system into the Bay of Bengal in ODP-117-758 site. Gupta and Srinivasan (1992) and Gupta and Fernandes (1994) presented paleomonsoonal and oceanographic changes respectively in term of higher sedimentation and the fresh water discharge during warmer periods associated with stronger monsoons corresponding to W-9 and W-11 warmer periods.

We have resolved two additional periods corresponding to W-10 (6.3-6.5 Ma) and W-8 (8.8-9.0 Ma) associated with salinity minima (Fig. 5). If the W-8 warmth and low salinity is followed by W-7 (~10 Ma) and W-6 (~11.3 Ma) in older geological samples, then the origin of monsoon may be older than previously at ~8.5 Ma (Prelt *et al.*, 1992), because the lowering of surface salinity is the first order oceanographic change due to monsoonal fresh water flux into the Bay of Bengal and the northeastern

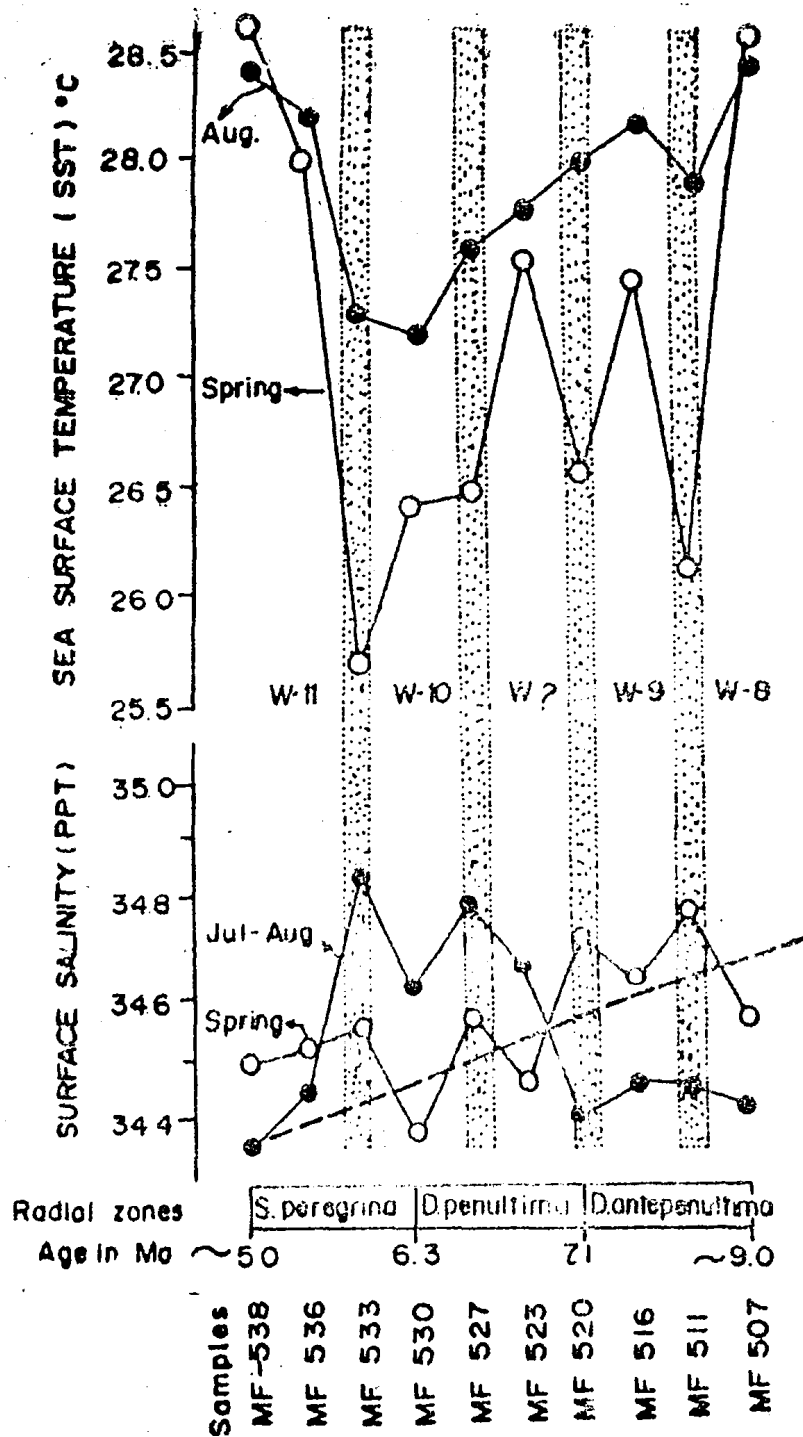
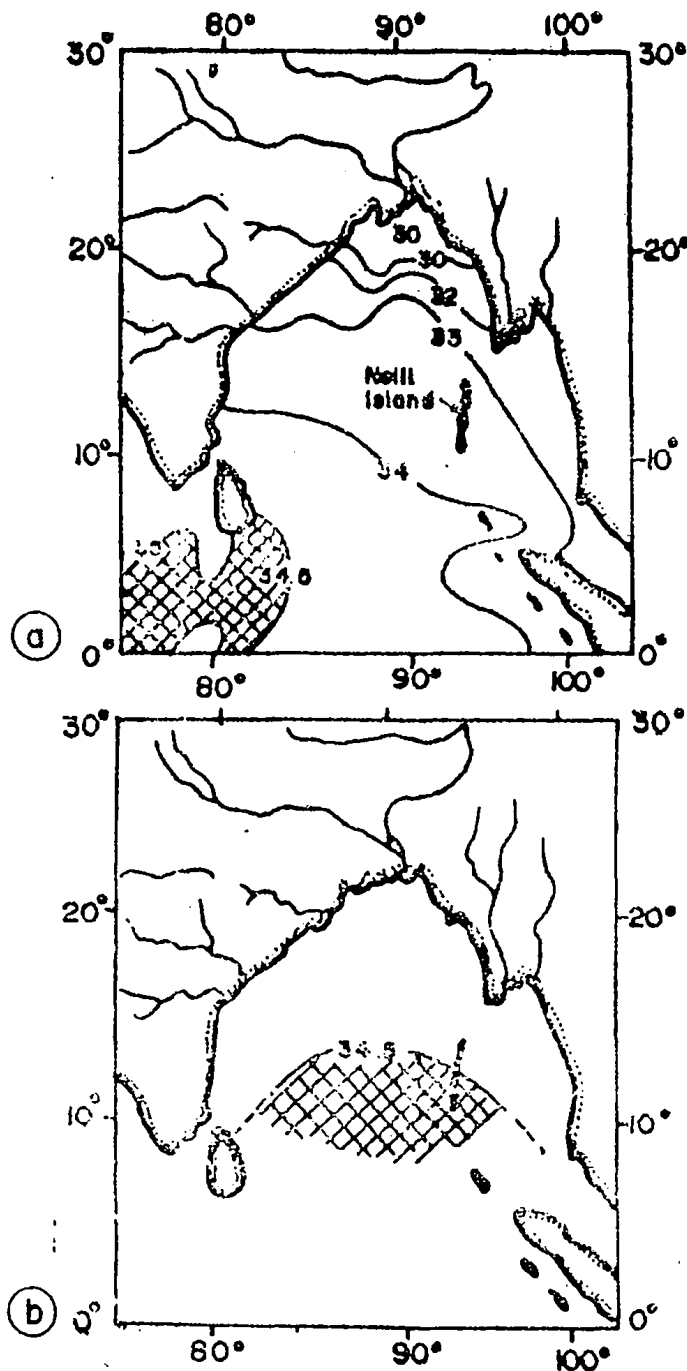


Fig. 5. Paleoestimates of SST-Spring and salinity-July-Aug. and salinity-spring in Sawai Bay Formation of Gupta and Srinivasan (1992). Broken line over salinity-Spring shows consistently lowering trend since 9.0-5.0 Ma suggesting the strengthening of monsoon in the late Miocene.



**Fig. 6.** Mean surface salinity during July-August in modern (a, after Wyrski, 1971) and mean of late Miocene over Neill Island (34.55ppt) Andamans in the Bay of Bengal (b). Note coverage of hypersaline water (crosshatched  $>34.5$ ppt) in modern time south of Sri Lanka (a) and its deeper intrusion into the Bay of Bengal in late Miocene (b). As monsoon strengthened hypersaline water was flushed out of the Bay of Bengal by the hyposaline water due to riverine fresh water flux during warmer periods analogous to modern time and reverse happened in the colder periods. Back and forth oscillation of hypersaline water in the way of Bengal shows paleomonsoonal salinity changes in the northeastern Indian Ocean.

Indian Ocean. The results are encouraging and suggest similar studies on closer samples to arrive an accurate timing of the first salinity drop due to the onset of monsoon in the late Miocene. We suggest that the changes in the atmospheric circulation from non-monsoonal to monsoonal one during late Miocene has resulted in torrential rains and riverine fresh water flux from the Indian subcontinent into the Bay of Bengal, that caused the salinity lowering at  $\sim 9.0$  Ma in the northeastern Indian Ocean. Consistently lowering trend in spring-salinity from 9.0-5.0 Ma suggest the strengthening of the monsoon in the late Miocene (Fig. 5).

### Conclusions

The % data of 25 broadly-defined taxonomic radiolarian groups has resulted in 4 Q-mode factors, i.e. SW, NE, transition and southern, explaining 89.15% variance. Factor-1 (hypersaline, cooler, highly productive), factor 2 (hyposaline, warmer, low productive), factor 3 (transition) and factor 4 (southern) define statistically sound water masses during southwest monsoon in the central tropical Indian Ocean. The curvilinear multiple regression analysis of factor loadings and the surface oceanographic variables of overlying water at the respective sampling sites, i.e. SST, salinity, PPP, derived the long-range transfer functions. We surmise that our transfer functions based on broadly defined supra-generic groups of radiolaria are potential for reliable estimates since late Miocene. Late Miocene paleoestimates of SST and salinity are conformable with the paleomonsoonal scenario described in Gupta and Srinivasan (1992) in addition to recognition of W 10 (6.3-6.5 Ma) and W-8 (9.0-9.2 Ma) warmer humid peaks. It

concur that SW monsoon was stronger during warmer periods between 5.5-9.0 Ma. The warmer humid monsoonal periods corresponds to W-8-11 warmer events of Barron and Keller (1983) and are the oldest monsoonal salinity record in Neogene. It is surmised that the changes in atmospheric circulation from non-monsoonal one has been very well reflected in the surface salinity because of monsoonal fresh water flux into the Bay of Bengal in the northeastern Indian Ocean  $\sim 9.0$  Ma. The Bay-of Bengal had a hypersaline ( $>34.5$  ppt) water mass during late Miocene that has been flushed out by hyposaline water due to the monsoon in modern time. Consistently lowering trend in spring-salinity suggests monsoonal strengthening 9.0 to 5.0 Ma since during the late Miocene.

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## References

- Barron, J.A. and Keller, G., 1983. Paleotemperature oscillations in the middle and latest Miocene of the northeastern Pacific. *Micropaleontol.*, 29: 150-181.
- Boltovskoy, D., 1987. Sedimentary records of radiolarian biogeography in the equatorial to antarctic western Pacific Ocean. *Micropaleontol.*, 33: 267-281.
- Burckle, L.H., 1989. Distribution of Diatoms in sediments of northern Indian Ocean: Relationship to physical oceanography. *Mar. Micropaleontol.*, 15: 53-65.
- Carroll, J., Falker, K.F., Brown, E.T. and Moore, W.S., 1993. Role of the Ganges-Brahmaputra mixing zone in supply of Barium and  $^{226}\text{Ra}$  to the Bay of Bengal. *Geochem. Cosmochim. Acta*, 57: 2918-2990.
- Clemens, J., Prell, W.L., Murray, D., Shimminfield, G. and Weedon, G., 1991. Forcing mechanism of the Indian Ocean Monsoon. *Nature*, 353: 720-725.
- CLIMAP project members, 1981. Seasonal reconstruction of earth's surface at last glacial maximum. *Geol. Soc. Am. Map and Chart Series*: 36 p.
- Cochran, J.R., 1990. Himalayan uplift, sea level and the record of Bengal fan sedimentation at ODP 116 sites. In: *Proc. ODP Sci. Res., 116, ODP-program*, College Station, TX: 397-414.
- COMMAP members, 1988. Climatic changes of the last 18,000 year: Observation and model simulations. *Science*, 242: 1043-1052.
- Cullen, J.L., 1981. Microfossil evidence for changing salinity pattern in Bay of Bengal over the last 20,000 years. *Paleoclimatol. Paleoecol.*, 35: 315-356.
- Dworetzky, B.A. and Morley, J.J., 1987. Vertical distribution of radiolaria in the eastern equatorial Atlantic: Analysis of a multiple series of closely-spaced plankton tows. *Mar. Micropaleontol.*, 12: 1-19.
- Fernandes, A.A. and Gupta, S.M., 1994. Statistical prediction of the late Miocene climate. *National Institute of Oceanogr., Goa, Tech. Rept. 5*: 1-87.
- Gupta, S. M., 1991. *Radiolarian distribution in surface sediments from the central Indian Ocean Basin and its paleoceanographic significance*. Goa University, 338 pp. + plates 18.
- Gupta, S.M. (in press) Quantitative radiolarian distribution in the surface sediments from the central Indian Ocean Basin and their paleomonsoonal significances. *J. Geol. Soc. India*.
- Gupta, S.M. and Fernandes, A.A., 1994. Coarser taxonomy based radiolarian transfer functions to estimate paleoceanographic changes since the Late Miocene in the tropical Indian Ocean. In: *VII INTER-RAD Conf.* Osaka, Japan: 47.
- Gupta, S.M. and Srinivasan, M.S., 1992. Late Miocene radiolarian biostratigraphy and paleoceanography of Sawal Bay Formation, Nicoll island, Andaman, India. *Micropaleontol.*, 38: 209-236.
- Gupta, S.M., Nigam, R. and Srinivasan, M.S., 1988. Cluster analysis of radiolarian fauna from Sawal Bay Formation, Andamans (late Miocene) and its paleoceanographic significance. In: *Geologia et Paleontologia, INTER-RAD-1/EURO-RAD-V conf.* Marburg Univ., Germany, July, 1988: 17.
- Hayes, P.L., Pisias, N.G. and Roelofs A.K., 1989. Paleoceanography of the eastern equatorial Pacific during the Pliocene: A high resolution radiolarian study. *Paleoceanogr.*, 4: 57-73.
- Imbrie J., and Kipp, N.G., 1971. A new micropaleontological method for quantitative paleoclimatology: Application to a late Pleistocene Caribbean core. In: *The late Cenozoic Glacial Ages*, K.K. Turkian, (Ed) Yale Univ. Press, New Haven, Conn.: 71-181.
- Imbrie, J., Donk, J.V. and Kipp, N.G., 1973. Paleoclimatic investigation of the late Pleistocene Caribbean deep sea core: comparison of isotopic and faunal methods. *Quaternary Res.*, 3: 19-38.
- Johnson, D.A., Schneider, D.A., Nigini, C.A., Cauet, J.P. and Kent, D.V., 1989. Pliocene-

- Pleistocene radiolarian events and magnetostratigraphic calibrations for the Tropical Indian ocean. *Amr. Micropaleontol.*, 14 : 33-66.
- Kling S.A., 1979. Vertical distribution of polycystine radiolarians in the central north Pacific. *Mar. Micropaleontol.*, 4 : 295-318.
- Klootwijk, C.T., Gee, J.S., Peirce, J.W. and Smith, G.M., 1992. Neogene evolution of Himalayan-Tibetan region : constraints from ODP site 758, northern 90°E Ridge, bearing on climatic changes. *Palaeogeogr. Palaeoclim. Palaeoecol.*, 95 : 95-110.
- Krey, J. and Babenerd, B., 1976. *Atlas of phytoplankton production, International Indian Ocean Expedition*, Keil Univ., Keil, 69p
- Levitus, S., 1982. Climatological atlas of the world oceans. *NOAA Prof. Papers*, Washington D.C., 13 : 173p
- Lombardi, G. and Boden, G., 1985. Modern radiolarian global distributions. *Cushman Found. Foram. Res. Spec. Publ.*, 16A : 126p.
- Lozano, J.A. and Hays, J.D., 1976. Relationship of radiolarian assemblages to sediment types and physical oceanography in the Atlantic and western Indian Ocean sectors of Antarctic Ocean. *Geol. Soc. Am. Mem.*, 145 : 303-336.
- Moore, T.C. Jr., 1973a. Method of randomly distributing grains for microscopic examination. *J. Sediment. Petrol.*, 43 : 904-906.
- Moore, T.C. Jr., 1973b. Late Pleistocene-Holocene oceanographic changes in the northeastern Pacific. *Quaternary Res.*, 3 : 99-109.
- Moore, T.C., Jr. 1978. The distribution of radiolarian assemblages in the modern and ice age Pacific. *Mar. Micropaleontol.*, 3 : 229-266.
- Moore, T.C., Jr. and Lombardi, G., 1981. Sea surface temperature changes in the North Pacific during the late Miocene. *Mar. Micropaleontol.*, 6 : 581-598.
- Moore, T.C. Jr., Burckle, L.H., Geitzenaure, K., Luz, B., Molina Cruz, A., Robertson, J.H., Sachs, H., Sancetta, C., Theide, J., Thompson, P. and Wenkam, C., 1980. The reconstruction of sea surface temperature in the Pacific Ocean of 18,000 years BP. *Mar. Micropaleontol.*, 5 : 215-247.
- Morley, J., 1979. A transfer function for estimating paleoceanographic conditions based on the deep-sea surface sediment distribution of radiolarian assemblages in the south Atlantic. *Quaternary Res.*, 12 : 381-395.
- Morley, J., 1989. Radiolarian based transfer functions for estimating paleoceanographic conditions in south Indian Ocean. *Mar. Micropaleontol.*, 13 : 293-308.
- Mullineaux, L.S. and Westberg-Smith, M.J., 1986. Radiolarians as paleoceanographic indicators in Miocene Monterey Formation, upper New Port Bay, California. *Micropaleontol.*, 32 : 48-71.
- Nigrini, C., 1991. Composition and biostratigraphy of radiolarian assemblages from an area of upwelling (NE Arabian Sea). *Proc. ODP, Sci. reports*, 117 : 89-126.
- Prell, W.L., Huston, W.H., William, D.F., He, A.W.H., Geitzenauer, F. and Molina, B., 1989. Surface circulation of the Indian Ocean during the last glacial maximum approximately 18,000 years B.P. *Quaternary Res.*, 14 : 309-336.
- Prell, W.L., Murray, D.W. and Clemens, S.C., 1992. Evolution and variability of the Indian Ocean Summer Monsoon : Evidence from the western Arabian Sea drilling program. *Geophys. Monogr.*, 70 : 447-469.
- Quade, J., Cerling, T.P. and Bowman, J.R., 1989. Development of monsoon revealed by marked ecological shift during latest Miocene in northern Pakistan. *Nature*, 342 : 163-166.
- Ravelo, A.C., Fairbank, R.G. and Philander, S.G.H., 1990. Reconstructing tropical Atlantic hydrography using planktonic foraminifera and an ocean model. *Paleoceanogr.*, 5 : 409-431.
- Rea, D.K., 1992. Delivery of Himalayan sediments to the northern Indian Ocean and its relation to global climate, sea level, uplift, and sea water strontium. *Geophys. Monogr.*, 70 : 387-402.

- Riedel, W.R., Westberg-Smith, M.J. and Budal, A., 1985. Late Neogene radiolaria and Mediterranean paleoenvironments. In: *Geological evolution of the Mediterranean Basin* Springer-Verlag: 487-523.
- Romine, K., 1985. Radiolarian biogeography and paleoceanography of the north Pacific since 8 Ma. *Geol. Soc. Am. Mem.*, 163: 237-272.
- Ruddiman, W. and Kutzbach, J.E., 1991. Plateau uplift and climate change. *Sci. American*, 264: 66-75.
- Takahashi, K., 1987. Radiolarian flux and seasonality: Climatic and El Nino response in the subarctic pacific, 1982-1984. *Global Biogeochemical Cycles*, 3: 213-231.
- Westberg-Smith, M.J., Tway, L.E. and Riedel, W.R., 1986. Radiolarians from the North Atlantic Ocean, DSDP Leg 94. *Intl. Rept. of the Deep Sea Drilling Project*, 94: 763-777.
- Wyrtki, K., 1971. *Oceanography atlas of the International Indian Ocean Expedition*. National Sci. Foundation, Washington D.C., 531 p.
- Wyrtki, K., 1973. Physical oceanography of the Indian Ocean. In: *The Biology of the Indian Ocean*, B. Zeitschel (Ed.). Springer-Verlag, New York: 18-36.

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