

Factors Controlling Vertical Fluxes of Particles in the Arabian Sea

T. M. BALAKRISHNAN NAIR¹, V. RAMASWAMY¹, G. PARTHIBAN¹ and R. SHANKAR²

¹National Institute of Oceanography, Dona Paula, Goa - 403004, India.

²Department of Marine Geology, Mangalore University, Mangalagangothri - 574199, India.

Abstract: Particle fluxes were measured using six time-series sediment traps at three sites in the western (16°20' N; 60°30' E), central (14°31' N; 64°46' E) and eastern (15°31' N; 68°43' E) Arabian Sea. Trap deployment depths were between 900 and 3000 m and collection period was from December 1992 to February 1994.

Annual particle fluxes showed an east-west trend with minimum fluxes (22.25 g m⁻²) in the eastern Arabian Sea and maximum fluxes (69.81 g m⁻²) in the western Arabian Sea. Carbonates, contributed mainly by foraminifers and coccolithophorids, are the dominant component in all the traps. Opal fluxes were maximum in the western Arabian Sea. At all the locations, lithogenic percentages increased with depth whereas organic carbon percentages decreased. Particle flux patterns show a strong seasonality with peak fluxes during the southwest (SW) monsoon (June to September). Relatively high fluxes were also observed during the northeast (NE) monsoon (December to February).

In the western Arabian Sea, particle fluxes are dominated mainly by carbonates during the early SW monsoon but by biogenic silica during the late SW monsoon. The increase in particle fluxes during the early SW monsoon is related to variations in the mixed layer depth which, in turn, is controlled by the strength of the Findlater Jet and the curl of the wind stress. The increase in biogenic silica fluxes during the late SW monsoon is related to the advection of nutrient-rich water from the Oman and Somali upwelling areas. In the eastern Arabian Sea, particle fluxes are high during the NE monsoon due to the effects of winter cooling.

Keywords: Oceanography, Particle flux, Sediment trap, Sea surface temperature, Arabian Sea.

INTRODUCTION

Particles settling in the ocean carry information on the aeolian and oceanic environment in which they are produced. To extract paleoceanographic information from sediments, it is necessary to study the processes controlling the production and settling of these particles in the present day oceans. Settling particles are composed mainly of aggregates of fine particles known as marine snow (Aldredge and Silver, 1988). They have a settling velocity ranging from a few metres to more than a kilometre per day. Settling particle fluxes at a given point can be determined in a simple manner by placing a receptacle, i.e., a sediment trap, in the water column. In recent years, time-series sediment traps have been extensively used to study particle fluxes in the ocean (Honjo, 1996). Particle flux studies in the northern

Indian Ocean started in May 1986 as an Indo-German collaborative project. These studies have yielded valuable information on the relationship between monsoon winds and particle flux (Nair et al. 1989; Ittekkot et al. 1991; Haake et al. 1993; Rixen et al. 1996), and on the coupling between lithogenic sedimentation process and biologic process (Ramaswamy et al. 1991; Ittekkot et al. 1991; Ramaswamy and Nair, 1994). Recently, the Joint Global Ocean Flux Studies (JGOFS) conducted in the Arabian Sea have shown a biological response to winter cooling (Madhupratap et al. 1996; Prasanna Kumar and Prasad, 1996).

In the present study, we have investigated the settling particles that were collected using PARFLUX sediment traps during 1993 from three stations in the Arabian Sea. The main

objective has been to identify the important factors controlling the production and settling of particles in the light of the recent JGOFS in the Arabian Sea.

MATERIALS AND METHODS

PARFLUX Mark VI sediment traps (Honjo and Doherty, 1988) were deployed at three sites in the western (16°20' N; 60°30' E), central (14° 31' N; 64° 46' E) and eastern (15°31' N; 68°43' E) Arabian Sea (Fig. 1) in May 1986. We present in this study, data on samples collected between December 1992 and February 1994. Details of trap locations, trap and water depths are depicted in Fig 1. Prior to deployment, the sampling cups were filled with filtered sea water from the mooring site and HgCl_2 (3.3 g l^{-1}) was added to prevent degradation of the trapped material.

Within a few hours of recovery, the sediment trap samples were wet-sieved through a 1 mm mesh size nylon sieve. Particles > 1 mm were usually large zooplankton carcasses, pteropod shells and occasionally large amorphous aggregates. This fraction, generally a few percent of the total flux, was not considered for the calculation of total flux. The <1 mm fraction

was split into 16 aliquots using a precision rotary splitter. No swimmers were picked up from the <1 mm fraction. The samples were filtered through $0.4 \mu\text{m}$ Nuclepore polycarbonate membrane filters, dried at 45°C and weighed to estimate the total fluxes. Carbonate was determined with a Carmograph (Wüstoff). Total carbon and nitrogen were analyzed using a Carlo Erba 1500 Carbon-Nitrogen Analyzer. Organic carbon was calculated as the difference between total carbon and carbonate carbon. Biogenic opal determination was based on a method modified from Mortlock and Froelich (1989). The decalcified sample was transferred to a clean polyethylene container, treated with 10 ml of 1 M sodium carbonate solution and kept in a water bath at 90°C for 2 hours. The extracted silica was measured spectrophotometrically by the molybdate blue method. Silica concentrations were multiplied by a factor of 2.4 to obtain the biogenic opal content (Mortlock and Froelich, 1989). Lithogenic fluxes were estimated from the weight of the material remaining after the removal of carbonate, organic matter (with 30% hydrogen peroxide solution) and opaline matter. Replicate analysis of a few samples showed that the mean variation is less than 1%.

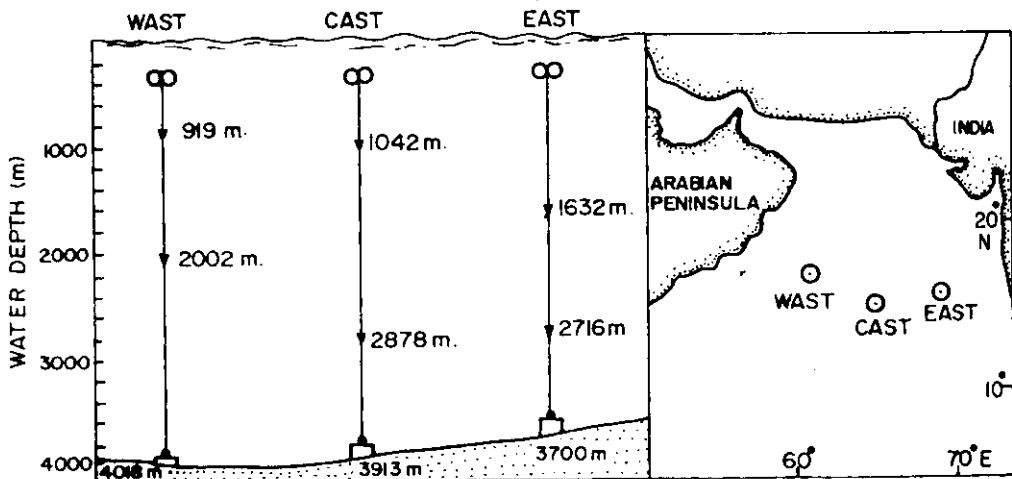


Fig. 1. Sediment trap mooring locations in the western (WAST), central (CAST) and eastern (EAST) Arabian Sea. Also shown is a schematic representation of sediment trap moorings, sediment trap and water depths.

RESULTS

trend from east to west and range from 69.81 g m⁻² y⁻¹ in the western Arabian Sea (shallow trap) to 22.25 g m⁻² y⁻¹ in the eastern Arabian Sea (shallow trap). In all the trap locations, carbonate fluxes are the highest (> 50 %) and organic carbon fluxes the lowest (<10%). The highest opal fluxes (~14.86 g m⁻² y⁻¹) recorded in the western Arabian Sea are six

The annual and seasonal fluxes of total and component materials are given in Table 1. Spatial variation of total and component fluxes and monthly variation of total fluxes are depicted in Figs. 2 and 3 respectively. The annual fluxes of particles show a decreasing

Table 1. Total and component fluxes of the <1 mm fraction in Arabian Sea Traps. All fluxes are in g m⁻²

Station, trap depth and season	Total flux	Carbonate flux	Opal flux	Litho-flux	C.org flux	Lith./C.org
Western Arabian Sea - 919 m						
NE monsoon	7.44	4.56	0.95	0.93	0.56	1.68
NE-SW inter-monsoon	8.27	4.94	1.09	0.95	0.72	1.32
SW monsoon	43.62	24.33	11.00	3.64	2.59	1.41
SW-NE inter-monsoon	10.48	6.36	1.82	1.06	0.69	1.54
Annual	69.81	40.19	14.86	6.58	4.55	1.45
Western Arabian Sea - 2002 m						
NE monsoon	12.50	9.35	2.49	1.93	0.88	2.21
NE-SW inter-monsoon	10.69	5.53	2.00	1.68	0.83	2.03
SW monsoon	25.43	13.58	6.64	2.62	1.44	1.82
SW-NE inter-monsoon	7.81	4.50	1.51	1.37	0.53	2.57
Annual	56.43	32.95	12.64	7.60	3.68	2.07
Central Arabian Sea - 1042 m						
NE monsoon	8.05	5.03	1.06	0.78	0.74	1.05
NE-SW inter-monsoon	7.01	3.89	1.23	0.73	0.84	0.86
SW monsoon	10.69	6.56	1.08	1.53	0.95	1.62
SW-NE inter-monsoon	4.09	2.37	0.52	0.63	0.47	1.35
Annual	29.83	17.85	3.89	3.66	3.00	1.22
Central Arabian Sea - 2872 m						
NE monsoon	9.70	5.87	1.29	1.49	0.55	2.72
NE-SW inter-monsoon	11.60	6.22	1.66	2.35	0.60	3.90
SW monsoon	18.92	11.67	2.49	2.99	0.64	4.69
SW-NE inter-monsoon	3.77	1.78	0.71	0.75	0.48	1.57
Annual	44.00	25.54	6.15	7.58	2.63	2.89
Eastern Arabian Sea - 1632 m						
NE monsoon	7.50	3.84	0.87	1.35	0.67	2.02
NE-SW inter-monsoon	4.12	2.85	0.30	0.54	0.24	2.28
SW monsoon	6.47	3.55	0.69	1.39	0.47	2.98
SW-NE inter-monsoon	4.15	2.09	0.47	0.86	0.51	1.69
Annual	22.25	12.33	2.33	4.15	1.88	2.20
Eastern Arabian Sea - 2716 m						
NE monsoon	6.95	3.71	0.85	1.66	0.41	4.10
NE-SW inter-monsoon	3.93	2.31	0.46	0.75	0.23	3.32
SW monsoon	7.02	4.11	0.79	1.44	0.38	3.81
SW-NE inter-monsoon	5.74	2.65	0.79	1.72	0.32	5.33
Annual	23.64	12.77	2.89	5.58	1.33	4.18

NE monsoon = December-February; NE-SW monsoon = March-May; SW monsoon = June-September; SW-NE monsoon = October-November

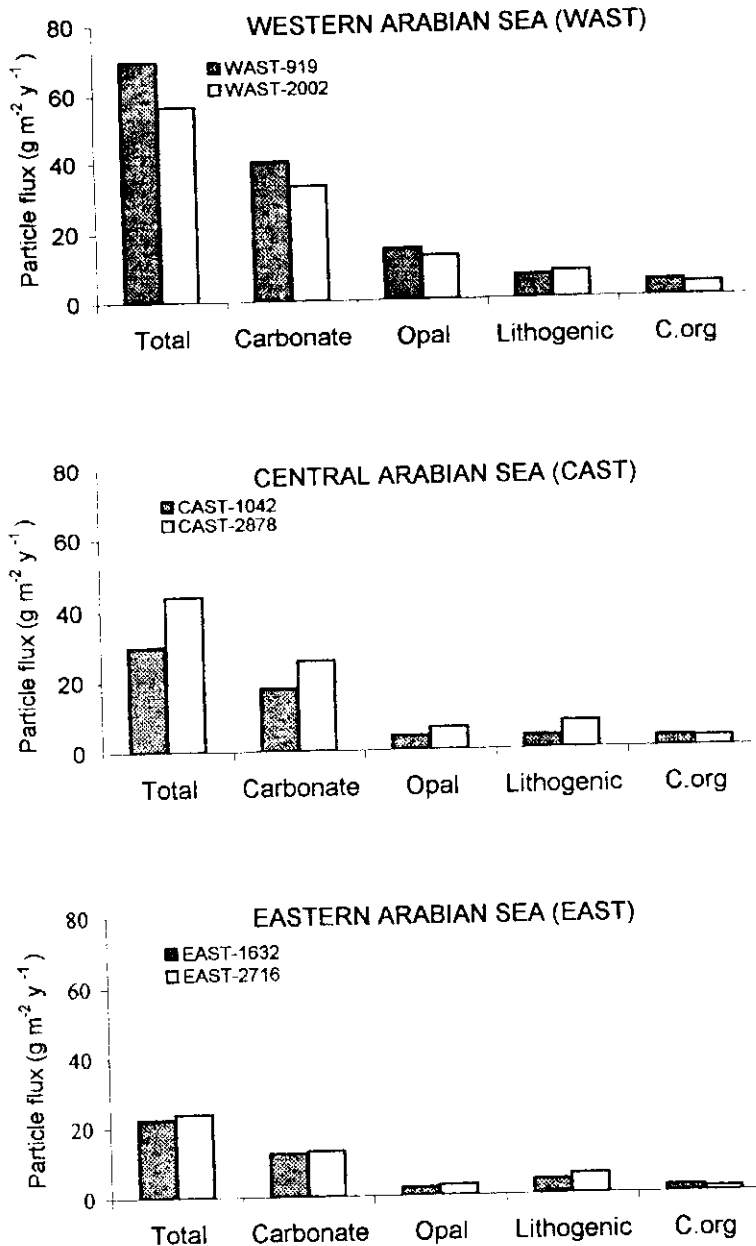


Fig. 2. Annual total, carbonate, opal, lithogenic and organic carbon fluxes in the eastern (EAST), central (CAST) and western (WAST) Arabian Sea.

times more than those in the eastern Arabian Sea.

Seasonal variation in particle fluxes has been noticed in all the trap locations. Fluxes during monsoons are generally higher than the inter-

monsoon periods. Monsoonal fluxes also show considerable spatial variation. In the western Arabian Sea, SW monsoon fluxes are remarkably higher than NE monsoon fluxes and account for ~ 65 % of the annual particle flux

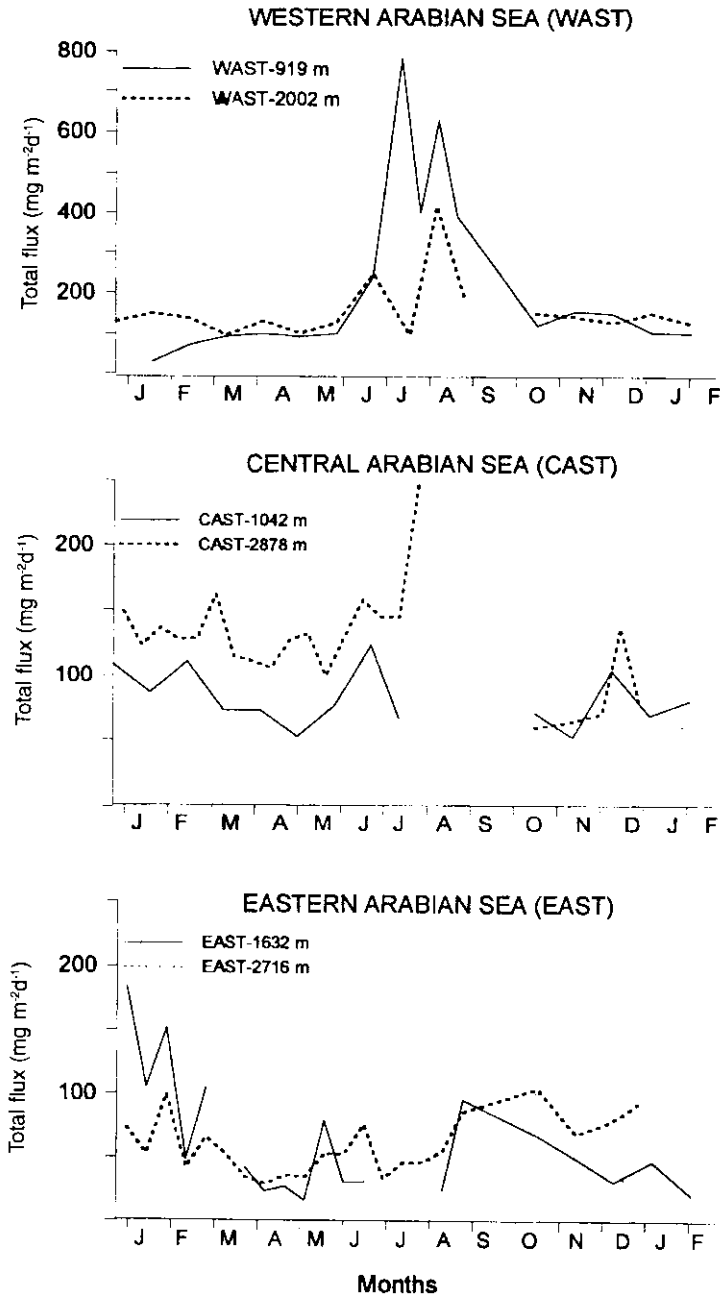


Fig. 3. Monthly variation of particle fluxes in the Arabian Sea traps.

(Fig. 3; Table 1). During the early SW monsoon, the carbonate fraction dominates whereas after a month the opaline flux increases significantly. In the eastern Arabian Sea, NE monsoon fluxes

are higher than the SW monsoon fluxes (Fig. 3).

Variability in the major component fluxes with depth has been noticed in all the trap

locations. As complete data set is not available for shallow trap during the SW monsoon, CAST is not considered for discussion relating to depth variations. There is a decrease in organic carbon flux with depth (Fig.2). In the western trap location, ~ 20 % reduction in the organic carbon flux was recorded from the shallow to the deep trap (from $4.55 \text{ g m}^{-2} \text{ y}^{-1}$ to $3.68 \text{ g m}^{-2} \text{ y}^{-1}$). The highest reduction (~ 33 %) of organic carbon flux (1.88 to $1.33 \text{ g m}^{-2} \text{ y}^{-1}$; Table 1) was recorded at the eastern trap location. Lithogenic fluxes show an increasing trend with depth; The increase is the lowest (~ 16 %) in the western Arabian Sea trap (6.58 to $7.60 \text{ g m}^{-2} \text{ y}^{-1}$) and the highest (~ 25 %) in the eastern Arabian Sea trap (from 4.15 to $5.58 \text{ g m}^{-2} \text{ y}^{-1}$).

DISCUSSION

Biogenic fluxes in the Arabian Sea

Annual particle fluxes at the western Arabian Sea trap location during 1993-94 are comparable to those reported for the Somali Basin during 1992-94 at similar depths (Weering et al. 1997). According to Nair et al. (1989), high fluxes during the SW monsoon are related to the increase in primary productivity caused by the wind-induced mixed layer deepening and the consequent nutrient injection to the euphotic zone. However, subsequent investigations revealed that the mixed layer dynamics and nutrient injection to the euphotic zone are related to the curl of the wind stress. Extreme conditions of atmospheric low during the SW monsoon produces the low level Findlater jet. This 200-400 km wide jet extends from Somalia to the Gujarat coast (Findlater, 1969). The area north of the Findlater jet is subjected to positive (cyclonic) wind stress curl (Hastenrath and Lamb, 1979). Hence, the mixed layer becomes shallow and nutrients are injected to the euphotic zone, leading to high biological productivity (Olson, 1991; Codispoti, 1991). The western Arabian Sea traps are situated in the area of positive wind stress curl which may be the cause for high particle fluxes in the western Arabian Sea.

Rixen et al. (1996) have shown recently that waters advected to the sediment trap area can either reduce or enhance productivity and particle fluxes depending upon whether the advected water is poor or rich in nutrients. According to these authors, during years with intense SW monsoon, the nutrient-poor South Equatorial water is advected to the western Arabian Sea. However, during normal SW monsoon years, nutrient-rich water from the Oman upwelling area is advected to this area. Morrison et al. (1998) observed that the advection of nutrient-rich water from the Oman coast to the open ocean takes place as filaments.

Sea surface temperature (SST) data for 1993 show that the upwelling signal is discernible during the last week of May at the Somali coast (Fig. 4a) and gets fully established by mid-June (Fig. 4b). At the Oman coast and the western Arabian Sea trap location, a drop in SST is noticed during June but a sharp decrease (indicative of intense upwelling) is seen only in July (Fig. 4c). However, the increase in total fluxes in the western Arabian Sea coincide with the onset of the SW monsoon in June. The particle fluxes during June and early July are dominated by carbonates which increase from $54.43 \text{ mg m}^{-2} \text{ d}^{-1}$ during May to $147.48 \text{ mg m}^{-2} \text{ d}^{-1}$ during June. This indicates that open ocean upwelling and shallowing of the mixed layer might have played a major role in nutrient pumping (mainly nitrates whose peak concentrations are observed at shallower depths when compared to silicates) and particle formation in the western Arabian Sea. US-JGOFS (Morrison et al. 1998) data also show that during early SW monsoon, the inorganic nitrate/silicate ratio is higher in the Arabian Sea (~ 1.6 compared to a normal ratio of 1) which favours carbonate-producing organisms. High fluxes during early SW monsoon may, therefore, be mainly due to the blooming of coccolithophores and foraminifers (mainly *Globigerina bulloides*; Curry et al. 1992) which are the main contributors of carbonate in the Arabian Sea.

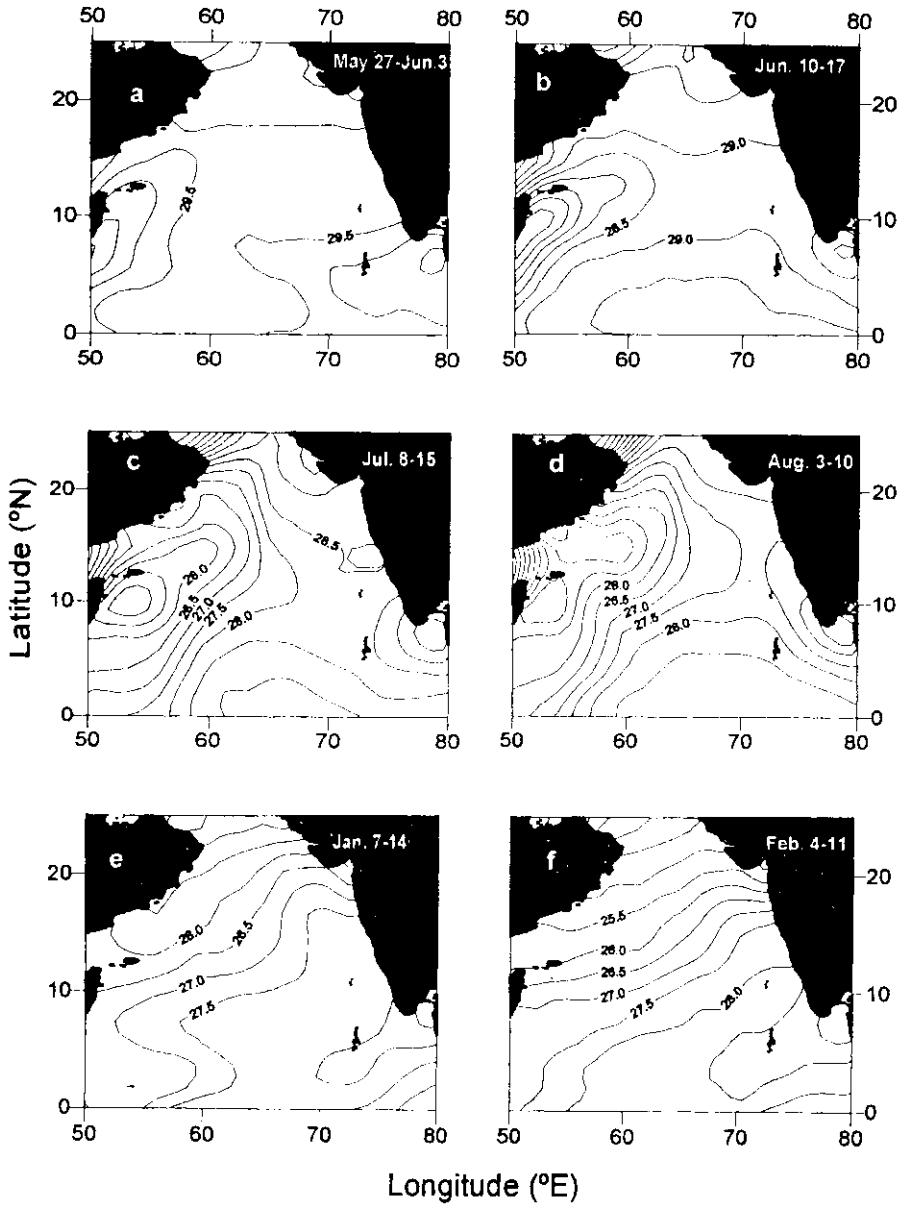


Fig. 4. Mean weekly sea surface temperature ($^{\circ}$ C) in the Arabian Sea during the 1993 SW monsoon (June-September) and NE monsoon (data analysis according to Reynolds and Smith, 1995).

An increase in opal flux was observed towards the end of July in the shallow western traps (between 21st July and 4th August). Biogenic silica is mainly contributed by *Rhizosolenia* and *Nitzschia* species (Rixen et al. 1996) which are well known upwelling

species; the high annual opal contribution (22 %) to the western Arabian Sea traps is an indication of the intense upwelled waters from below 150 meters (Haake et al. 1993).

The maximum depth of the Arabian Sea mixed layer is about 120 m and water from

below 150 m is brought to the surface only in coastal upwelling areas. High opal fluxes in the western Arabian Sea trap location should be due to the advection of silica-rich waters from coastal upwelling centers. Recently, Morrison et al. (1998) have shown that low salinity waters from the Oman upwelling zone are advected towards the central Arabian Sea and sink to about $25 \sigma_{\theta}$ during the late SW monsoon. Although the Oman upwelling centre is the most likely source, it could well be that silica-rich waters from the Somali upwelling centre advected over the western Arabian Sea trap site.

The clockwise-flowing Indian Monsoon Current (Tchernia, 1980), the Somali Current in the western Arabian Sea (Schott et al. 1990) and the North Equatorial Current bring waters from the south into the northern Arabian Sea. The influence of the Somali current is clearly seen up to 8°N . The region north of 8°N has not been studied in detail but climatological data (Conkright et al. 1994) show the intrusion of these waters from the equatorial Indian Ocean into the western Arabian Sea up to 16°N . The western Arabian Sea trap site is located about 900 km away from the Somali upwelling center. SST charts (Fig. 4a) show that upwelling started in the Somali coast during the last week of May 1993. If we assume an advection velocity of 0.28 m s^{-1} (Prasanna Kumar, pers. comm.), the advected water from the Somali coast can reach the western trap in about 40 days, i.e., by the beginning of July and can support the high opal fluxes observed at this site in the third week of July.

The central Arabian Sea trap is located near the center of the Findlater Jet (Olson, 1991). Mixed layer depth at this site is normally >100 metres. The curl of the wind stress at this site can be positive or negative as the axis of the Findlater Jet can shift to the north or south. As a consequence, nutrient injection and particle production can show sharp variations during the SW monsoon or on an inter-annual basis. This site can also be affected by advection from the Oman and Somali upwelling centers though not

as much as the western site. Deep trap shows a slight increase in opal fluxes during August (Fig. 3) which may be attributed to the diatom bloom.

Particle fluxes in the eastern Arabian Sea are the lowest when compared to the central and western Arabian Sea. The main reason for this could be the less intense upwelling and advection here during that year. Upwelling up to 15°N has been reported along the west coast of India (Sharma, 1978) during SW monsoon. In August 1993, upwelling signals were apparent in the SW coast of India (Fig. 4d) and consequently a slight increase in fluxes was observed in the eastern Arabian Sea. Interestingly, particle fluxes during the study period were higher during NE monsoon. Satellite data show that SST in the northern Arabian Sea decreases continuously during January and February 1993 (Figs. 4e and f) due to winter cooling. The JGOFS program has shown that winter cooling and the associated convective mixing is the main mechanism by which productivity is enhanced in the Arabian Sea during the NE monsoon (Madhupratap et al. 1996; Prasanna Kumar and Prasad 1996; Morrison et al. 1998). During most of the years, the warm, nutrient-poor waters from the equatorial Indian Ocean cover the eastern Arabian Sea trap area (Haake et al. 1993). This can reduce the intensity of convective mixing and input of nutrients to the euphotic zone. During 1993, the effect of this water mass may have been less and the convective overturning more intense, thus enhancing the particle fluxes.

Lithogenic Fluxes in the Arabian Sea

The main sources of lithogenic material to the Arabian Sea are the Indus, the Narmada and the Tapi rivers and aeolian input from the Somali-Arab deserts (Kolla et al. 1981; Shankar et al. 1987; Sirocko and Sarin, 1989). The surface sediments off Arabia have a high content of aeolian quartz ($>30\%$). Based on clay mineralogical studies of the sediment trap samples, Ramaswamy et al. (1991) have

suggested that the eolian material derived from the Somali-Arab deserts cover the entire Arabian Sea. Our data set shows that about 55 % of the annual lithogenic flux to the western Arabian Sea trap is received during the SW monsoon (Table 1). According to Sirocko (1993), 91% of the annual dust transport takes place during June - August and is controlled by the monsoon winds. The eolian flux of $7.1 \text{ g m}^{-2} \text{ y}^{-1}$ calculated by Duce et al. (1991) corresponds with the lithogenic flux recorded for the western Arabian Sea trap. Proximity to the aeolian source material may be the reason for the high lithogenic fluxes in the western region. Lithogenic fluxes in the eastern Arabian Sea were higher during both the NE and SW monsoons. The deep trap shows the highest lithogenic fluxes during the SW-NE inter-monsoonal period (Table 1).

Most of the lithogenic matter reaching the open ocean is in the form of fine particles like clay flakes which can not sink on their own (Lal, 1977). Lithogenic fluxes, however, increase with depth (Fig.2) because lithogenic matter can be aggregated by the sticky organic mucous coating (Lal, 1977; Alldredge and Silver, 1988) and can settle along with marine snow. Studies on the association of Transparent Exopolymers (TEP) and terrigenous matter (Kumar et al. 1998) provides direct evidence for the 'ballast hypothesis' (Ittekkot et al. 1991) i.e., the role of terrigenous particles in increasing the export of organic carbon to the deep sea floor. The lithogenic to organic flux ratio, which reflects the importance of biological processes in the transport of lithogenic particles (Ramaswamy et al. 1991), varies from 0.65 to 6 in the Arabian Sea trap samples.

CONCLUSIONS

1. Particle fluxes during 1993 in the Arabian Sea showed an increasing trend from east to west. High fluxes were mostly during the SW monsoon in the western Arabian Sea and during NE and NE-SW inter-monsoonal period in the eastern Arabian Sea.
2. Open ocean upwelling and advective process appear to control the particle fluxes in western Arabian Sea traps. Particle fluxes are dominated mainly by carbonate during early SW monsoon but by biogenic silica during late SW monsoon. High opaline silica fluxes in the western Arabian Sea are related mainly to the advection of nutrient-rich waters from the Oman and Somali upwelling centres.
3. In the eastern Arabian Sea, convective mixing due to winter cooling enhances the particle fluxes during NE monsoon.
4. There is a biological control on lithogenic sedimentation process which increases the lithogenic fluxes with depth.

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References

- ALLDREDGE, A. L. and SILVER, M. (1988). Characteristics, dynamics and significance of marine snow. *Progress in Oceanography*, v. 20, pp. 41-82.
- CODISPOTI, L. A. (1991). Primary productivity and carbon and nitrogen cycling in the Arabian Sea. Arabian Sea Process Study. US-JGOFS Planning Rept. no. 13, pp. 49-54.
- CURRY, W. B., OSTERMAN, D. R., GUPTHA M. V. S. and ITTEKOT, V. (1992). Foraminiferal production and monsoonal upwelling in the Arabian Sea: Evidence from sediment traps. *In: Upwelling systems: Evolution since the early Miocene*. C. P. Summerhayes, W. L. Prell, and K. C. Emeis (Eds.), Geol. Soc. London, Spec. Publ., no. 64, pp. 93-106.

- CONKRIGHT, M. E., LEVITUS, S., BOYER, T. P. and LUTHER, M. E. (1994). Atlas of Northern Indian Ocean. NOAA/NODC, University of South Florida, Washington, D. C.
- DUCE, R. A., LISS, P. S., MERRILL, J. T., ATLAS, E. L., BUAT-MENARD, P., HICKS, MILLER, B., PROSPERO, P., ARIMOTO, R., CHURCH, T. M., ELLIS, W., GALLOWAY, J. N HANSEN, L., JICKELLS, T. D., KNAP, A. H., RAINHARDT, K. H., SCHNEIDER, B., SOUDINE, A., TOKOS, J. J., TSUNOGAI, S., WOLLAST, R. and ZHOU, M. (1991). The atmospheric input of trace species to the World Ocean. *Global Biogeochemical Cycles*, v. 5, pp. 193-259.
- FINDLATER, J. (1969). A major low level air current near the Indian Ocean during the Northern Summer. *Quat. Jour. Royal Met. Soc.*, v. 95, pp. 362-380.
- HAAKE, B., ITTEKKOT, V., RIXEN, T., RAMASWAMY, V., NAIR, R. R. and CURRY, W. B. (1993). Seasonality and inter-annual variability of particle fluxes to the deep Arabian Sea. *Deep-Sea Research*, v. 40, pp. 1323-1344.
- HASTENRATH, S. and LAMB, P. J. (1979). *Climate Atlas of the Indian Ocean, Part 1*. University of Wisconsin Press, Madison, USA, 97 charts.
- HONJO, S. (1996). Fluxes of particles in the interior of the open ocean. *In: Particle flux in the Ocean*. Ittekkot, V., Schafer, P., Honjo, S. and Depetris, (Eds.), John Wiley & Sons, pp. 91-145.
- HONJO, S. and DOHERTY, K. W. (1988). Large aperture time-series sediment traps: design, objectives, construction and application. *Deep-Sea Research*, v. 35, pp. 133-149.
- ITTEKKOT, V., NAIR, R. R., HONJO, S., RAMASWAMY, V., BARTSCH, M., MANGANINI, S. and DESAI, B. N. (1991). Enhanced particle fluxes in Bay of Bengal induced by injection of fresh water. *Nature*, v. 351, pp. 385-387.
- KOLLA, V., RAY P. K. and KOSTECKI, J. A. (1981). Surficial sediments of the Arabian Sea. *Marine Geol.*, v. 41, pp. 183-204.
- KUMAR, M. D., SARMA, V. V. S. S., RAMAIAH, N., GAUNS, M. and DE SOUSA, S. N. (1998). Biogeochemical significance of transparent exopolymer particles in the Indian Ocean. *Geophys. Res. Lett.*, v. 25, pp. 81-84.
- LAL, D. (1977). The oceanic microcosm of particles. *Science*, v. 198, pp. 997-1009.
- MADHUPRATHAP, M., PRASANNA KUMAR, S., BHATTATHIRI, P. M. A., KUMAR, M. D., RAGHU KUMAR, S., NAIR, K. K. C. and RAMAIAH, N. (1996). Mechanism of the biological response to winter cooling in the northeastern Arabian Sea. *Nature*, v. 384, pp. 549-552.
- MORRISON, J. M., CODISPOTI, L. A., GAURIN, S., JONES, B., MANGANINI, V. and ZHENG, Z. (1998). Seasonal variation of hydrographic and nutrient field during the Arabian Sea Process Study. *Deep-Sea Research II*, v. 45, pp. 2053-2101.
- MORTLOCK, R. A. and FROELICH, P. N. (1989). A simple method of rapid determination of biogenic opal in the pelagic marine sediments. *Deep-Sea Research*, v. 36, pp. 1415-1426.
- NAIR, R. R., ITTEKKOT, V., MANGANINI, S. J., RAMASWAMY, V., HAAKE, B., DEGENS, E. T., DESAI, B. N. and HONJO, S. (1989). Increased particle fluxes to the oceans related to the monsoons. *Nature*, v. 338, pp.749-751.
- OLSON, D. B. (1991). Mixed Layer Dynamics in the Arabian Sea. *Arabian Sea Process Study US-JGOFS Planning Rept. no. 13*, pp. 49-54.
- PRASANNA KUMAR, S. and PRASAD T. G. (1996). Winter cooling in the Northern Arabian Sea. *Curr. Sci.*, v. 71, pp. 834-841.
- RAMASWAMY, V., NAIR, R. R., MANGANINI, S., HAAKE, B. and ITTEKKOT, V. (1991). Lithogenic fluxes to the deep Arabian Sea measured by sediment traps. *Deep-Sea Research*, v. 38, pp. 169-184.
- RAMASWAMY, V. and NAIR, R. R. (1994). Fluxes of material in the Arabian Sea and Bay of Bengal - Sediment trap studies. *In: Biogeochemistry of the Arabian Sea: Present Information and Gaps*. D. Lal (Ed.), Indian Acad. Sci., v. 103, pp. 189-210.
- REYNOLDS, R. W. and SMITH, T. M. (1995). A high resolution global sea surface temperature climatology. *Jour. Climate*, v. 8, pp. 1571-1683.
- RIXEN, T., HAAKE, B., ITTEKKOT, V., GUPTHA, M. V. S., NAIR, R. R. and SCHLUSSEL, P. (1996). Coupling between SW monsoon-related surface and deep ocean processes as discerned from continuous particle flux measurements and correlated satellite data. *Jour. Geophys. Res.*, v. 101, pp. 569-582.
- SCHOTT, F., SWALLOW, J. C. and FIEUX, M. (1990). The Somali current at the equator: Annual cycle of currents and transports in the upper 1000 m and connection to neighbouring latitudes. *Deep-Sea Research*, v. 37, pp. 1825-1848.
- SHANKAR, R., SUBBARAO, K. V. and KOLLA, V. (1987). Geochemistry of surface sediments from the Arabian Sea. *Marine Geol.*, v. 76, pp. 253-279.
- SHARMA, G. S. (1978). Upwelling off the southwest coast of India. *Indian Jour. of Marine Sci.*, v. 7, pp. 209-218.
- SIROCKO, F. and SARNTHEIN, M. (1989). Wind-borne deposits in the northwestern Indian Ocean: Record of Holocene sediments versus modern satellite data. *In: Paleoclimatology and Palcometeorology: Modern and Past Patterns of Global Atmospheric Transport*. Leinen, N. and Sarnthein, M. (Eds.), pp. 401-433.
- SIROCKO, F. (1993). Aerosol dust in late Quaternary sediments of the Northern Indian Ocean. *In: Monsoon Biogeochemistry*. V. Ittekkot and R. R. Nair (Eds.), SCOPE/UNEP International Carbon Unit, University of Hamburg, Germany, pp. 185-192.
- TCHERNIA, P. (1980). *Descriptive Regional Oceanography*. Pergamon Press, Oxford, 253p.
- WEERING, T. C. E. V., HELDER, W. and SCHALK, P. (1997). The Netherlands Indian Ocean Expedition 1992-1993: First results and introduction. *Deep-Sea Research*, v. 44, pp. 1177-1193.

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