

Distribution of particulate organic carbon in the central Arabian Sea

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MS received 25 September 1987; revised 22 June 1988

Abstract. Particulate organic carbon (POC) of 161 water samples collected from 8 depths (surface to 1000 m) at 21 stations was measured. The POC concentrations ranged from 154 to 554 μg per litre at the surface and decreased in the upper 300 m water column. At greater depths (> 300 m), POC concentrations increased and were similar (145 to 542 $\mu\text{g l}^{-1}$) to those observed at surface. Deep water POC maximum was embedded within the oxygen minimum layer and was also associated with high phosphate-phosphorus. The POC contents increased, whereas oxygen decreased as the distance away from the shore increased. Phytoplankton biomass was a major source of POC. The observed pattern of POC is discussed with respect to some physicochemical and biological factors.

Keywords. Particulate organic carbon; chlorophyll *a*; dissolved oxygen; Arabian Sea.

1. Introduction

In the open ocean, particulate organic matter (POM) is mostly derived from surface primary production by phytoplankton and consists of autotrophic and heterotrophic organisms and their detritus. Therefore, POM constitutes a major part of the total suspended material in the surface waters of the ocean (Lal 1977). It plays an important role in the vertical transport of organic and inorganic materials and also serves as a sink for some trace components such as heavy metals and organic pollutants (Lal 1977; Sackett 1978; Simpson 1982). POM consists of large particles such as fecal pellets (Urrere and Knauer 1981) and marine snow (Asper 1987), which rapidly settles to the sea floor. Recent studies based on Carbon-14 data suggest that these rapidly sinking particles are not the major source of organic carbon for organisms in deep waters (Pearcy and Stuiver 1983). Such particles are rare in the seawater (McCave 1975), and therefore, poorly collected by conventional water samplers. They are, however, collected more effectively by sediment traps or filtering large volumes of seawater at depths (McCave 1975). The other type comprises slowly sinking small particles ($< 50 \mu\text{m}$) that dominate the standing stock of POM. These small particles are generally collected using conventional water samplers.

Studies on the distribution and composition of small particles, collected by water sampling bottles, have been carried out in many seas and oceans (Riley 1970; Menzel 1974; Copin-Montegut and Copin-Montegut 1983; Gordon and Cranford 1985). Earlier studies on the distribution of POM showed that it varies little and is refractory below a depth of 300 m (Menzel 1974). Later studies reported that both particulate organic carbon (POC) and nitrogen (PON) varied spatially and temporally (Riley 1970; Gordon *et al* 1979), and decreased with depth (Copin-Montegut and Copin-Montegut 1983; Gordon and Cranford 1985). It was also observed that deep water concentrations

of POC were correlated with surface primary production (Wangersky 1976; Gordon 1977; Gordon and Cranford 1985).

Compared to large POC data collected over the years from different oceanic regions, very little information is available on the POC distribution in the waters of the Arabian Sea. Studies made so far are restricted to the euphotic zone (Radhakrishna *et al* 1978a, b; Bhattathiri and Devassy 1979).

Recently, we reported the distribution of POC in the central Bay of Bengal (Nandakumar *et al* 1987). In continuation of our studies on the distribution of POC in the northern Indian Ocean, we present here the POC data from the oceanic waters of the Arabian Sea. The general features emerging from the results are discussed with respect to some physicochemical and biological parameters.

2. Materials and methods

Seawater samples (161) were collected using Niskin water samplers (5–10 l) from eight depths (0 to 1000 m) at 21 stations during 13 B cruise of *ORV Sagar Kanya* in the central Arabian Sea from 14 February to 14 March 1985 (figure 1). Samples were immediately filtered through pre-combusted (450°C 3 h) 47 mm GF/C (1.0 µm pore size) glass filters. Filters were stored at -20°C until the analysis was completed. Particulate matter left on the filters was analysed for POC and chlorophyll *a* (Chl *a*). As the filters were not preweighed, suspended matter could not be determined on these samples.

POC was analysed spectrophotometrically after wet oxidation of carbon by acid dichromate (Parsons *et al* 1984). Chl *a* was estimated spectrofluorometrically after extracting the filters with 90% acetone (Boto and Bunt 1978). Dissolved oxygen was determined by Winkler method (Carpenter 1965). Inorganic phosphate-phosphorus was analysed on a six-channel autoanalyser (Skalar) on board the vessel. The precision of these methods was better than $\pm 6\%$.

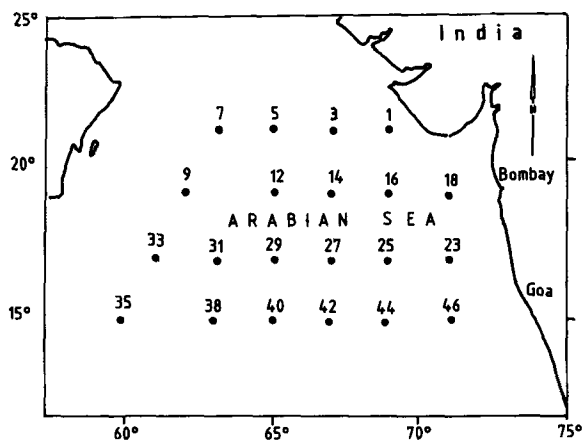
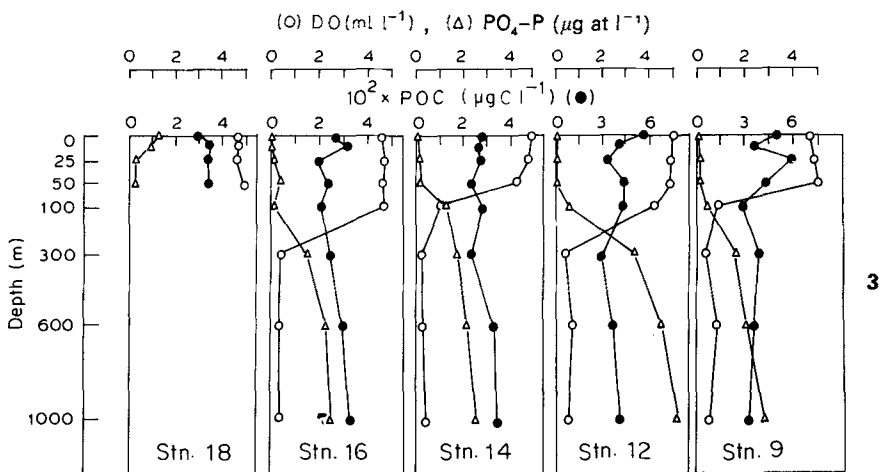
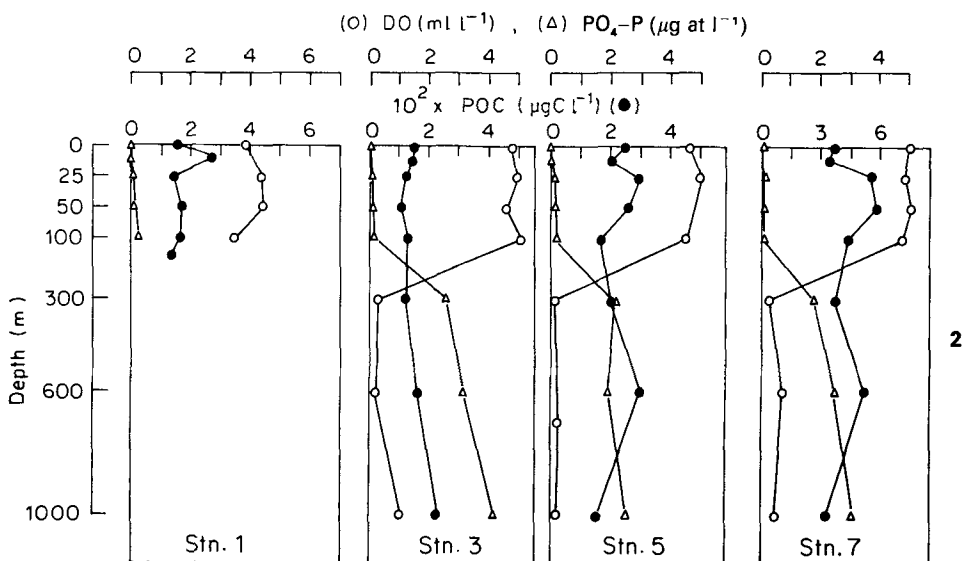


Figure 1. Location of sampling sites in the Arabian Sea.

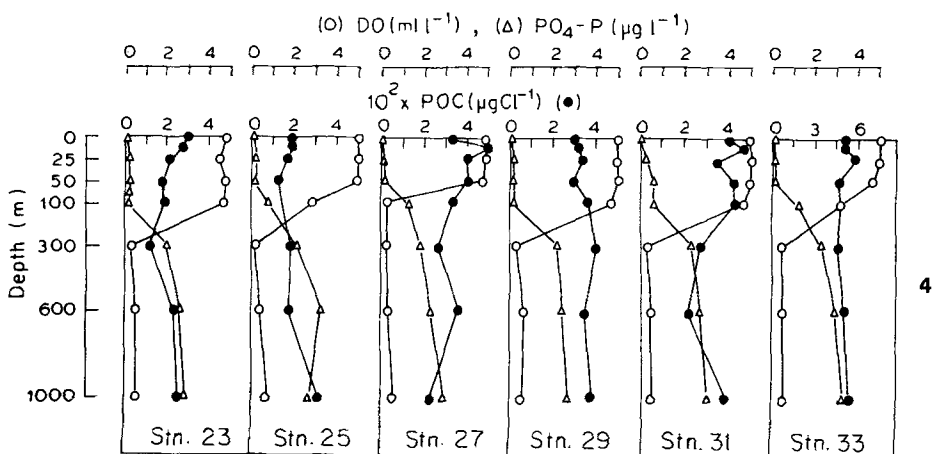
3. Results and discussion

Vertical profiles of POC, dissolved oxygen and inorganic phosphate-phosphorus are shown in figures 2 to 5. These data are also given in appendix 1. The range of minimum and maximum concentrations of these parameters for all the stations along with standard deviations and coefficients of variation are given in tables 1-3.

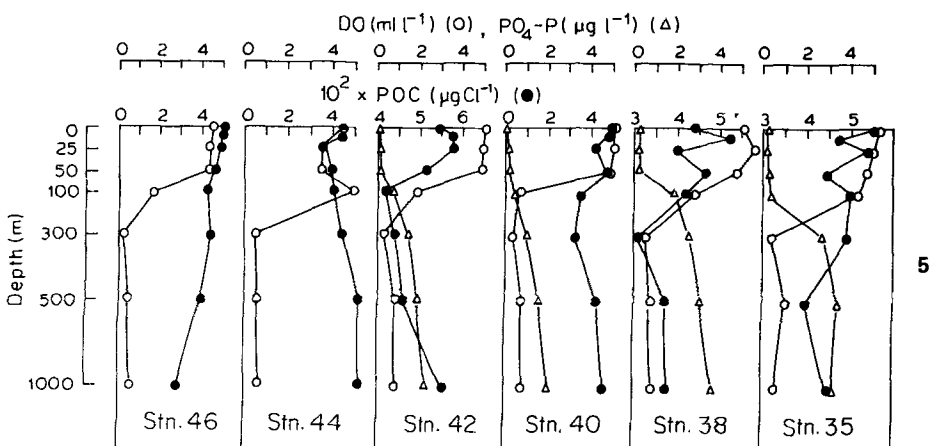
Surface POC concentrations ranged from 154-554 $\mu\text{g l}^{-1}$ ($\bar{x} = 368 \pm 125 \mu\text{g l}^{-1}$; $n = 21$). These values are in the same range as those reported earlier from the surface waters of the Arabian Sea (Radhakrishna *et al* 1978a, b; Bhattathiri and Devassy 1979) as well as from other areas (Romankevich 1984). With some exceptions the concentrations of POC generally decreased with increasing depth in the upper 300 m water column (figures 2 to 5). This probably suggests loss of carbon during descent due



Figures 2-3. For caption, see next page.



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Figures 2–5. Concentration of POC, dissolved oxygen (DO) and inorganic phosphate-phosphorus (PO_4) vs depth profiles in the Arabian Sea.

Table 1. Distribution of particulate organic carbon (μgCl^{-1}) at different stations in the Arabian Sea.

Depth (m)	Range	Mean	SD	CV %	<i>n</i>
0	155–554	368	125	33.96	21
10	149–568	373	118	31.63	21
25	105–581	359	143	39.83	21
50	103–581	350	132	37.71	21
100	124–490	323	116	35.91	20
300	109–481	307	109	35.50	19
600	155–510	343	99	28.86	19
1000	145–542	340	105	30.88	19

SD, standard deviation; CV, coefficient of variation; *n*, number of samples.

Table 2. Distribution of dissolved oxygen (ml l^{-1}) at different stations in the Arabian Sea.

Depth (m)	Range	Mean	SD	CV %	n
0	3.99–5.22	4.81	0.27	5.61	21
10	—	—	—	—	—
25	4.30–5.50	4.85	0.27	5.56	21
50	4.31–5.10	4.72	0.22	4.66	21
100	0.20–5.07	3.25	1.62	49.84	20
300	0.07–0.36	0.23	0.09	39.31	19
600	0.19–0.87	0.44	0.20	45.45	19
1000	0.12–1.06	0.43	0.19	44.18	19

SD, standard deviation; CV, coefficient of variation; n, number of samples; —, no data.

Table 3. Distribution of inorganic phosphate-phosphorus ($\mu\text{g at l}^{-1}$) at different stations in the Arabian Sea.

Depth (m)	Range	Mean	SD	CV %	n
0	tra–1.30	0.12	0.28	233.30	19
10	—	—	—	—	—
25	tra–0.38	0.10	0.12	120.00	19
50	tra–0.57	0.15	0.16	106.60	19
100	tra–1.74	0.56	0.47	83.92	18
300	0.93–3.30	2.00	0.54	27.00	17
600	1.39–4.40	2.56	0.68	26.56	17
1000	1.90–5.00	2.90	0.74	25.51	17

SD, standard deviation; CV, coefficient of variation; n, number of samples; —, no data; tra, traces below detection limit.

to remineralization, ingestion and assimilation by mid-water organisms. Throughout the water column, POC varied by about a factor of 5 (table 1). This probably indicates uniform supply of organic matter as a result of diatom bloom during the period of sampling. Diatom blooms are generally observed in February/March in the Arabian Sea (Kelkar, personal communication).

At most of the stations, after an initial decrease in the upper 300 m water column, the POC concentrations generally increased, especially from 600 to 1000 m depth (figures 2 to 5), and were more or less similar to those observed at the surface (table 1). These deep water POC concentrations observed for the Arabian Sea are higher than those reported from other areas (Wangersky 1976; Copin-Montegut and Copin-Montegut 1983; Romankevich 1984; Gordon and Cranford 1985). Nevertheless, these values are in the same range as those reported recently for the Bay of Bengal (Nandakumar *et al* 1987). Higher concentrations of POC observed here are probably due to higher surface primary production in the area (Qasim 1977).

With few exceptions vertical profiles of POC (figures 2 to 5) observed here are significantly different from those reported by Menzel (1974), and more recently by Gordon and Cranford (1985). In his review, Menzel (1974) opined that POC

concentrations decreased very little and are homogeneous below a depth of 300 m. In contrast to this, Gordon and Cranford (1985) suggested that POC decreased with depth. The present result disproves both and implies that POC distribution in Arabian Sea is more complicated than that reported from other regions (Menzel 1974; Wangersky 1976; Copin-Montegut and Copin-Montegut 1983; Gordon and Cranford 1985). Probably some physicochemical and biological conditions prevailing during sampling in the Arabian Sea play an important role in influencing the distribution of POC in these waters.

Sinking rates of organic detrital particles depend on the particle density and viscosity of fluid medium. Rapid changes in temperature and salinity are reported from Arabian Sea waters (Sengupta and Naqvi 1984) which may alter the density and decrease the sinking rate of organic detritus particles causing probably an accumulation (Karl *et al* 1976). However, in that case we would expect the accumulation of POC in the upper 100 to 200 m water column where density gradients were maximum (Sengupta and Naqvi 1984).

A second mechanism that might explain the observed pattern of POC distribution involves a relaxation of upwelling followed by subsequent injection of surface-derived particulate matter into the mesopelagic zone. Garfield *et al* (1979) proposed such a model to account for subsurface peaks in suspended protein at 200 to 250 m depth. In our present study we were unable to resolve any subsurface peaks in POC; thus, it seems unlikely that we have observed temporally uncoupled patches of organic matter originating at the surface.

The secondary peak observed for POC (figures 2 to 5) might also be due to chemolithotrophic microbial growth and carbon production at these depths (Karl and Knauer 1984). However, such a mechanism has been contested by others (Betzer *et al* 1984).

Migrating zooplankton populations have been implicated in the removal and transfer of organic matter. It was observed that zooplankton abundance is larger in the top 200 m than at greater depths (Paulinose and Arvindakshan 1977). There was no significant difference in the zooplankton biomass between the hauls taken from 200 to 0 m and 900 to 0 m implying that the organisms are largely confined to upper 200 m and tend to avoid the oxygen-deficient layer below 300 m. This pattern of zooplankton distribution is very well reflected in the POC distribution. Thus, it is likely that the secondary POC peak observed at 600 to 1000 m depth is due to dearth of zooplankton at these depths.

Alternatively, this secondary POC peak was due to lateral transport of organic matter from the productive shelf. In order to check this possibility we have integrated the POC values in the depth range of 0 to 100 m, 300 to 600 m and 1000 m and plotted them against distance away from the shore (figure 6). A simple regression analysis was also used to assess the significance of this relationship. Throughout the water column, POC concentrations increased as the distance away from the shore increased. A positive correlation coefficient was observed which was significant ($P \leq 0.001$). However, the r values were slightly low. This positive relationship between POC and the distance away from the shore suggests lateral transport of POC from the productive shelf waters and might be the possible process for the accumulation of POC in deep waters.

Elevated POC values in low oxygenated waters could also be the result of conversion of dissolved organic carbon to POC. In any case a secondary POC maximum exists

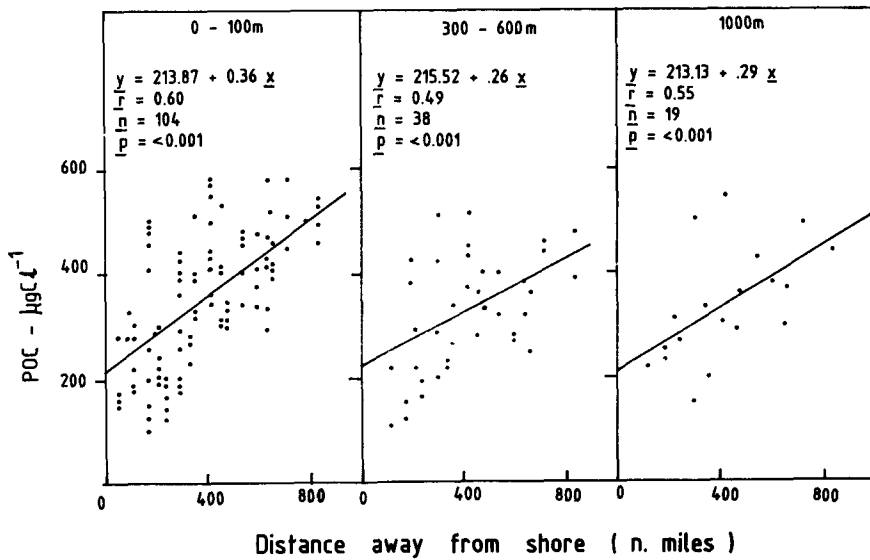


Figure 6. Relationship between POC and distance away from shore.

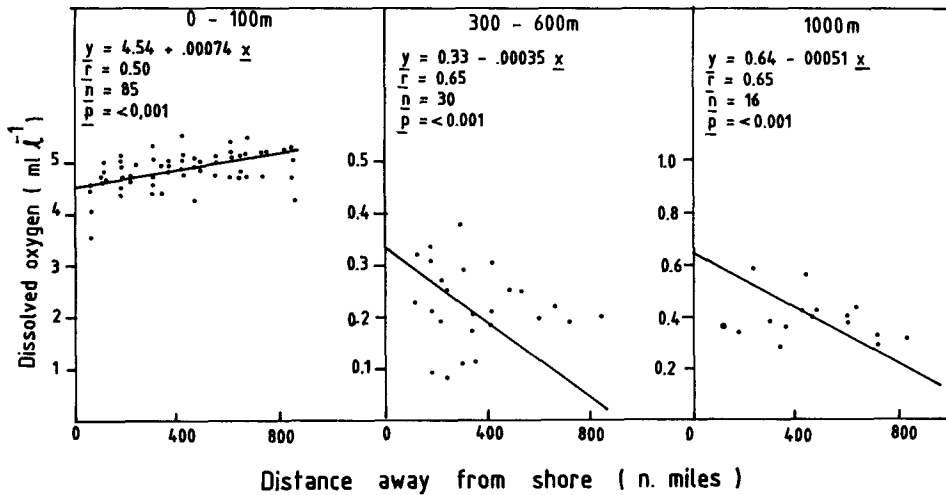


Figure 7. Relationship between dissolved oxygen and distance away from shore.

because the supply of POC to these depths exceeds the loss, because of either increased supply or decreased loss.

The *in situ* concentration of dissolved oxygen represent a balance between vertical and horizontal diffusion and advection and biological utilization (Riley 1951). Distribution of dissolved oxygen in the study area is shown in figures 2 to 5. A mean concentration of 4.81 ml l^{-1} of dissolved oxygen was observed for the surface waters which decreased with depth and a minimum of 0.23 ml l^{-1} was observed at about 300 m (table 2). In the upper 0 to 100 m water column no significant changes in the oxygen concentrations were observed (figure 7). Below 300 to 1000 m, oxygen concentrations

decreased as the distance away from the shore increased (figure 7). An oxygen minimum layer extending from 300 to 1000 m was very conspicuous (figures 2 to 5, table 2). A deep water POC maximum was found embedded within this layer. Once the organic matter gets accumulated as mentioned above, it is oxidised, thus depleting the oxygen concentration. This is evident from the inverse distribution pattern of dissolved oxygen and POC (figures 2 to 5), probably suggesting biological utilization.

At 300 m, however, this is not the case as low oxygen concentration is generally accompanied by a minimum of POC content at most of the stations (figures 2–5). This can probably be explained as follows. The high salinity water in the Persian Gulf characterized by σ_t values of 26.6 flows throughout the Hormuz Strait and the Gulf of Oman into the Arabian Sea and maintains its density level at about 300 m depth (Sengupta and Naqvi 1984). More or less in the same depth range the intensive zone of denitrification has been reported (Sengupta and Naqvi 1984). As the oxygen concentration is very low, nitrate ions are the next abundant source of free energy for the oxidation of organic matter (Richards 1965). Probably this is what is happening at this depth. Thus, low POC concentrations observed at 300 m and subsequent nitrite maximum at more or less same depth (Sengupta and Naqvi 1984) suggests the possibility that low POC concentration at 300 m is the result of POC oxidation using nitrate as the electron acceptor.

Below this depth (> 300 m), the dissolved oxygen is minimum and POC maximum and inorganic phosphate-phosphorus also start increasing (figures 2 to 5). Phosphate-phosphorus was low in the surface waters ($0.12 \mu\text{g at l}^{-1}$) and increased rapidly with depth to a maximum of $2.90 \mu\text{g at l}^{-1}$ (table 3). The microbial decomposition of accumulated organic matter proceeds with utilization of oxygen and release of phosphate-phosphorus (figures 2 to 5). It is reported that phosphate-phosphorus maximum usually lies close to oxygen minimum and CO_2 maximum (Riley and Chester 1971). In the Arabian Sea CO_2 maximum lies in the O_2 minimum zone, although the phosphate-phosphorus maximum is slightly below O_2 minimum zone (Sengupta and Naqvi 1984).

In oceanic waters, POM is mostly derived from the surface primary production by phytoplankton and consists of autotrophic and heterotrophic organisms and their detritus. Chl *a* has been used as an indicator of phytoplankton biomass. Detailed distribution of Chl *a* will be dealt separately (Pant, personal communication). Here, these data are only used to assess the contribution of Chl *a* carbon to POC. A regression analysis was used to find out the relationship between these two parameters. A significant relationship between these two parameters ($P \leq 0.001$) was found ($r = 0.62$; $n = 82$; $Y = 223.82 + 15.28 X$), indicating that phytoplankton carbon comprised a fairly constant percentage of total carbon.

Acknowledgements

The authors thank Dr B N Desai for constant encouragement. We also thank Dr A Pant for providing us unpublished Chl *a* data and to Shri N S Parabhu for his help on board the ship. We also appreciate the comments offered by the referee which helped us in improving the manuscript.

Appendix 1. Concentrations of POC, DO and PO₄ - P at various stations in the Arabian Sea.

Station	Depth (m)	POC $\mu\text{gC l}^{-1}$	DO ml l^{-1}	PO ₄ - P $\mu\text{g at l}^{-1}$
1	0	154.94	3.99	0.05
	10	276.46	4.02	0.01
	25	148.86	4.36	0.01
	50	173.16	4.38	tra
	100	164.05	3.56	0.32
	150	142.94	—	—
3	0	154.94	4.71	0.12
	10	148.86	—	—
	25	115.44	4.97	tra
	50	103.29	4.64	0.16
	100	124.56	5.07	0.22
	300	124.30	0.31	2.63
	600	154.94	0.21	3.12
	1000	227.85	1.06	4.17
5	0	261.27	4.71	tra
	10	206.58	—	tra
	25	288.61	5.10	0.21
	50	264.34	4.71	0.25
	100	174.16	4.50	0.20
	300	197.47	0.11	1.95
	600	285.57	0.22	2.07
	1000	145.82	0.12	2.49
7	0	364.55	4.98	tra
	10	336.20	—	—
	25	550.19	4.78	tra
	50	581.27	5.10	tra
	100	441.52	4.77	0.07
	300	372.41	0.18	1.97
	600	510.38	0.62	2.45
	1000	303.80	0.42	2.99
9	0	477.97	4.60	0.08
	10	342.28	—	—
	25	581.27	4.82	0.14
	50	421.27	5.03	0.16
	100	293.67	0.80	0.45
	300	376.71	0.34	1.60
	600	338.23	0.80	2.33
	1000	303.80	0.45	2.85
12	0	534.69	5.09	tra
	10	405.07	—	—
	25	311.90	4.94	tra
	50	423.29	4.92	tra
	100	415.19	4.25	0.50
	300	275.45	0.36	3.30
	600	358.48	0.65	4.40
	1000	394.67	0.40	5.00

(Appendix 1. Continued)

14	0	281.02	4.95	0.05
	10	265.83	—	—
	25	273.42	4.89	0.05
	50	232.41	4.37	0.36
	100	279.50	1.06	1.15
	300	227.85	0.17	1.80
	600	318.99	0.20	2.18
	1000	332.66	0.28	2.54
16	0	264.31	4.66	0.01
	10	305.32	—	—
	25	189.88	4.74	tra
	50	235.45	4.66	0.40
	100	200.51	4.71	tra
	300	240.00	0.27	1.50
	600	293.17	0.19	2.10
	1000	308.36	0.23	2.30
18	0	281.02	4.60	1.30
	10	329.62	4.65	0.92
	25	325.07	4.56	0.34
	50	329.62	4.45	0.30
23	0	303.80	4.76	0.02
	10	282.53	—	—
	25	215.70	4.50	tra
	50	182.28	4.77	tra
	100	192.91	4.66	0.10
	300	109.37	0.23	1.90
	600	215.70	0.41	2.40
	1000	233.29	0.35	2.60
25	0	191.40	4.89	0.10
	10	197.47	—	—
	25	159.50	4.90	0.20
	50	123.04	4.87	tra
	100	139.75	2.82	0.70
	300	185.32	0.07	2.00
	600	159.50	0.25	3.20
	1000	273.42	0.58	2.70
27	0	320.51	4.88	tra
	10	507.35	—	—
	25	391.90	4.97	tra
	50	399.50	4.76	0.10
	100	326.59	0.20	1.20
	300	258.23	0.11	1.70
	600	343.29	0.20	2.20
	1000	208.10	0.35	2.80
29	0	297.72	4.99	0.02
	10	306.84	—	—
	25	335.70	4.98	0.27
	50	290.13	5.01	0.10
	100	349.37	4.76	0.19
	300	397.98	0.25	2.11
	600	331.14	0.51	2.40
	1000	355.45	0.42	2.50

(Appendix I. Continued)

31	0	389.31	5.10	tra
	10	478.48	—	—
	25	343.29	5.09	0.38
	50	410.13	5.00	0.57
	100	422.28	4.69	0.60
	300	282.53	0.20	2.36
	600	265.83	0.42	2.77
	1000	376.71	0.39	2.97
33	0	508.86	5.10	0.28
	10	508.86	—	—
	25	580.26	5.08	0.18
	50	452.66	4.71	0.26
	100	476.97	3.31	1.35
	300	443.55	0.30	2.30
	600	461.71	0.47	2.93
	1000	492.16	0.33	3.15
35	0	554.43	5.22	0.31
	10	464.81	—	—
	25	528.61	4.97	0.15
	50	461.78	4.72	0.20
	100	490.64	4.22	0.32
	300	481.52	0.20	2.67
	600	385.83	0.87	3.22
	1000	435.95	0.33	2.92
38	0	432.92	5.01	0.06
	10	519.50	—	—
	25	393.42	5.50	0.10
	50	461.78	4.77	0.13
	100	410.13	2.72	1.74
	300	252.15	0.36	2.39
	600	363.04	0.52	2.93
	1000	366.08	0.60	3.45
40	0	481.52	4.97	tra
	10	472.40	—	—
	25	402.53	5.00	tra
	50	464.81	4.72	tra
	100	340.26	0.65	0.52
	300	320.51	0.34	0.93
	600	401.02	0.69	1.39
	1000	431.40	0.60	1.95
42	0	531.65	5.00	tra
	10	568.10	—	—
	25	569.62	4.98	tra
	50	504.31	4.44	—
	100	397.98	4.95	—
	300	422.28	0.29	—
	600	508.86	0.38	—
	1000	499.75	0.38	—
46	0	501.27	4.50	—
	10	490.64	—	—
	25	478.48	4.30	—
	50	458.74	4.31	—
	100	411.65	1.53	—
	300	432.91	0.09	—
	600	381.27	0.33	—
	1000	249.16	0.34	—

—, no data; tra, traces could not be detected; DO, dissolved oxygen.

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