

# Coccolithophores from the central Arabian Sea: Sediment trap results

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Sediment trap samples collected from a depth of 1018 m in the Central Arabian Sea Trap (CAST) at 14°28.2'N, 64°35.8'E were analyzed for temporal variation of coccolithophore fluxes from October 1993 to August 1994. Out of the twenty species of coccolithophores encountered, *Gephyrocapsa oceanica*, *Emiliana huxleyi*, *Umbellosphaera sibogae* and *Umbellosphaera irregularis* were the most abundant. The total coccolithophore fluxes ranged from  $28.5 \times 10^6 \text{ m}^{-2}\text{d}^{-1}$  to  $50.3 \times 10^6 \text{ m}^{-2}\text{d}^{-1}$  showing seasonality with higher fluxes during the northeast (NE) monsoon and lower fluxes during the spring intermonsoon. The higher fluxes were attributed to the enhancement of primary production in the central Arabian Sea due to southward extent of nutrients from the northeast Arabian Sea by the prevailing surface currents. Similarly, the occurrences of relatively lower coccolithophore fluxes during the spring intermonsoon and southwest (SW) monsoon were attributed to the low nutrients in the warm, shallow surface mixed layer and downwelling to the south of Findlater Jet respectively in the central Arabian Sea. Some of the coccolithophore species such as *E. huxleyi*, *G. oceanica*, *Calcidiscus leptoporus* and *Umbellosphaera tenuis* showed signs of dissolution.

## 1. Introduction

Coccolithophores are one of the major primary producers and one of the most important groups, of microplankton contributing to the phytoplankton community in the oceans. Generally, the coccolithophores dominate in the stratified waters of the tropical and subtropical regions (Brand 1994). However, there have been many reports on their abundant occurrences within the mixed layer (Kleijne 1993; Giraudeau *et al* 1993). The coccolithophores are useful to interpret the hydrographic conditions and the extent of primary productivity in the study regions. These coccolithophores convert dissolved carbon dioxide in the ocean into calcium carbonate ( $\text{CaCO}_3$ ). The pathway from production of this mineral at the

sea surface to its deposition on the sea floor is an important process and is an essential variable in the global carbon cycle (Broerse *et al* 2000; Ziveri *et al* 2000). Coccolithophores are also known to influence the global climate through emission of dimethylsulphide (Westbroeck *et al* 1993). Owing to the fact that the mass of a single coccolith is about  $8 \times 10^{-6} \mu\text{g}$  with a surface area of  $32 \mu\text{m}^2$  and settling velocity of  $1.6 \mu\text{m/s}$  (or  $13.8 \text{ cm/d}$ ), the sedimentation to the ocean floor is a complex process (Steinmetz 1994). Therefore, the slow descent rate and large area of a coccolith increases its residence period in the water column resulting in rapid dissolution of coccolithophores (Honjo 1975; Steinmetz 1994). However, fecal pellets and other oceanic macroaggregates are the main carriers for the rapid vertical transport of

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the majority of coccolithophores through undersaturated waters to the sea-floor (Honjo 1975, 1980). The typical sinking speeds of larger particles are of the order of 100 to 200 m/d (Waniek *et al* 2000). Understanding the export of living coccolithophore assemblages and their ecological significance as they sink from the euphotic zone to the seafloor are essential in the studies of paleoceanography and paleoclimate. Earlier studies on coccolithophores from the Arabian Sea were largely confined to the sediment (Andruleit and Rogalla 2002). However, Kleijne (1993); Guptha *et al* (1995); Zeltner (1998); Andruleit *et al* (2000, 2003) and Schiebel *et al* (2004) studied living flora from water samples. Subsequent studies on coccolithophores using sediment trap samples were limited to the northwestern Arabian Sea (June 1992–February 1993) by Broerse *et al* (2000) and northeastern Arabian Sea (October 1993–February 1994 and May 1995–February 1996) by Andruleit *et al* (2000). In this context, the present study is focused on the sediment trap samples collected from the central Arabian Sea to understand the living coccolithophores and their ecological implications in relation to the semi-annually reversing monsoons and the associated hydrographic conditions.

## 2. Hydrography of the central Arabian Sea

The Arabian Sea falls under the influence of semi-annually reversing monsoons – the northeast (NE) monsoon (winter monsoon) during November–February and the southwest (SW) monsoon (summer monsoon) during June–September. These semi-annual monsoon winds drive strong surface currents and the associated upper layer circulation reverses with season (Wyrtki 1973; Mariano *et al* 1995; Shankar *et al* 2002). The seasonal surface drift currents (Mariano *et al* 1995) during January and July (figure 1a–b), representing the NE and SW monsoons respectively, show a southwestward flow towards the central Arabian Sea (study area) from the northeast coast of India in January and an eastward flow emanating from the western Arabian Sea towards central Arabian Sea in July. During SW monsoon, the low-level Findlater Jet (Findlater 1969) with high intensity of southwesterly winds crosses over central Arabian Sea in the SW–NE direction (Madhupratap *et al* 1996; Manghnani *et al* 1998; Prasanna Kumar *et al* 2001a), i.e., north of the sediment trap location at 14°N (shown by solid square in figure 1a and 1b). Under the influence of the Findlater Jet, surface winds are strong over the central Arabian Sea, which in turn plays a vital role in the

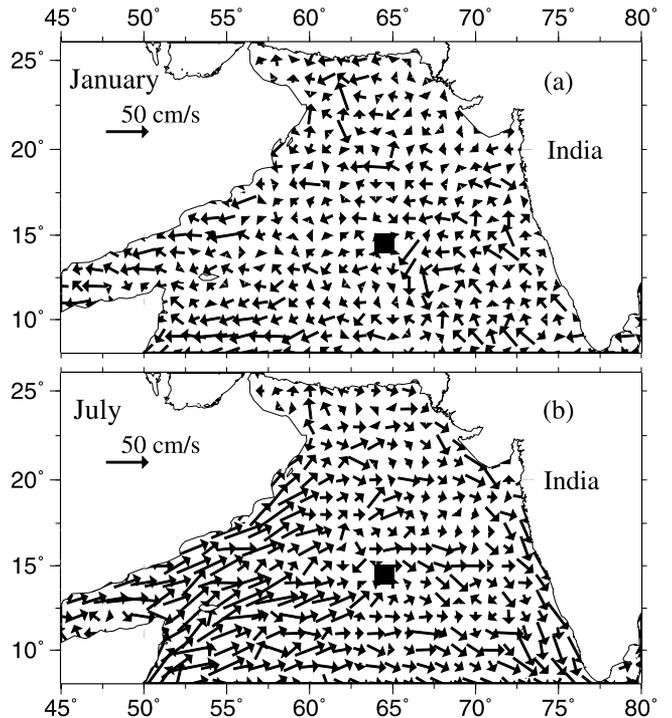


Figure 1. Surface current vectors derived from ship drifts in the Arabian Sea during (a) January and (b) July. (After Mariano *et al* 1995.) The sediment trap location is depicted as a solid square.

oceanic and air–sea interaction processes (Flagg and Kim 1998; Manghnani *et al* 1998; Morrison *et al* 1998; Prasanna Kumar and Narvekar 2005). Morrison *et al* (1998) reported seasonal variation of sea surface temperature, sea surface salinity, mixed layer depth, subsurface water masses and inorganic nitrogen (nitrate + nitrite + nitrogen) for the period between September 1994 and December 1995 in the Arabian Sea. Furthermore, they have shown that a large part of central Arabian Sea exhibits a deep mixed layer (100–120 m) and elevated concentration of nitrates during both the NE and SW monsoons. Winter cooling at the sea surface due to enhanced evaporation and decrease in solar radiation caused deepening of the mixed layer and an elevation of nutrients by entrainment within the upper oceanic layer (Prasanna Kumar and Prasad 1996; Morrison *et al* 1998). During SW monsoon, concentration of inorganic nitrogen (mostly nitrates) was high in the upwelling zone off Oman and decreased towards the central Arabian Sea, which was, however, relatively high compared to the eastern Arabian Sea (Morrison *et al* 1998). Prasanna Kumar and Narvekar (2005) discussed seasonal variability of mixed layer depth as a result of wind forcing and its implication to the variability of nutrients, chlorophyll-*a* and primary productivity in the central Arabian Sea along 64°E section and inferred prevalence of intense upwelling to the north of the Findlater Jet axis

and downwelling to its south (Prasanna Kumar *et al* 2001b; Prasanna Kumar and Narvekar 2005 and the relevant references therein) during SW monsoon. They further reported higher concentration of nitrate ( $1\ \mu\text{M}$ ) at shallow depths (20 m) with higher surface chlorophyll-*a* ( $1.0\ \text{mg}/\text{m}^3$ ) to the north of the Jet axis ( $17^\circ\text{N}$ – $19^\circ\text{N}$ ). During NE monsoon the cold and dry winds from the north-east induce increased cooling of surface waters near the Gulf of Oman and along the Pakistan shelf leading to intense wind mixing and the associated entrainment results in higher nitrate concentration ( $1$ – $3\ \mu\text{M}$ ) in the surface layer north of  $15^\circ\text{N}$ , along with elevated surface chlorophyll-*a* leading to high biological productivity (Qasim 1982; Smith *et al* 1991; Madhupratap *et al* 1996; Prasanna Kumar *et al* 2000). During spring intermonsoon (March–May), the mixed layer depth is shallow ( $\sim 30\ \text{m}$ ) due to thermal stratification because of higher sea surface temperatures and intense solar radiation (Prasanna Kumar and Narvekar 2005). These authors also found low concentrations of chlorophyll-*a* and depleted nutrients in the upper layer, suggesting the prevalence of oligotrophic conditions in the central Arabian Sea during spring intermonsoon (Morrison *et al* 1998). Compared to SW monsoon, surface circulation is less vigorous during NE monsoon and wind-induced mixing ventilates only the top of the oxygen minimum zone (Madhupratap *et al* 1996; Morrison *et al* 1998). The US JGOFS measurements showed higher primary productivity both during NE monsoon ( $1$ – $2\ \text{gCm}^{-2}\text{d}^{-1}$ ) and SW monsoon ( $1.5\ \text{gCm}^{-2}\text{d}^{-1}$ ) periods (Smith *et al* 1998).

### 3. Material and methods

As part of the Indo-German collaborative program, a cruise onboard *ORV Sagar Kanya* (SK-98) was organized to deploy Mark VI time series sediment trap mooring in the central Arabian Sea ( $14^\circ 28.2'\text{N}$  :  $64^\circ 35.8'\text{E}$ ) at 1018 m in a water column of 3914 m (figure 1). The sampling period was scheduled for 18 October 1993 to 5 October 1994 with sampling intervals of 27 days. Prior to the deployment, sampling cups were filled with *in situ* seawater collected from the trap depth to which 35 g/l NaCl and 3.3 g/l  $\text{HgCl}_2$  were added for preservation and poisoning to prevent biodegradation. Immediately after recovery, these samples were stored in cold storage at  $4^\circ\text{C}$ . The supernatant solution was decanted and the residue was wet sieved through a  $> 1\ \text{mm}$  mesh sieve, the fraction  $< 1\ \text{mm}$  was then split into aliquot of 1/4 to 1/18 of the total sample volume. The samples were then filtered onto pre-weighed nucleopore filters

( $0.4\ \mu\text{m}$ ) and dried at  $45^\circ\text{C}$ . A small portion of the dried filter was cut and placed on a sample stub, coated with gold/palladium ( $100\ \text{\AA}$ ) in a sputter coater and scanned using Joel SEM Model 5800 LV, for coccolithophore species identification and quantification. Utmost care was taken to ensure that the particles were distributed in a monolayer on the filter. The number of coccospheres and coccoliths were then counted at a higher magnification of 3500 for 15–20 fields of view with a minimum count of 350–800 cells depending on their availability. Total coccolithophore (coccolith and coccosphere) fluxes ( $\times \text{Nos}/\text{m}^2/\text{day}$ ) were calculated by extrapolating the counted specimens for the total sample, duration of trap and aperture area.

The  $\text{CaCO}_3$  flux of coccolith was estimated by multiplying the specific weight of each coccolith species by their corresponding fluxes (Broerse *et al* 2000). Similarly,  $\text{CaCO}_3$  flux of coccospheres was also estimated by multiplying the coccosphere fluxes by the mean number of coccoliths and their specific coccolith weight (Broerse *et al* 2000).

### 4. Results

This study yielded twenty species of coccolithophores with a total flux of coccoliths ranging from  $28.5 \times 10^6\ \text{m}^{-2}\text{d}^{-1}$  to  $50.3 \times 10^6\ \text{m}^{-2}\text{d}^{-1}$  (tables 1 and 2). Among them, *Gephyrocapsa oceanica*, *Emiliana huxleyi*, *Umbellosphaera sibogae* and *Umbellosphaera irregularis* were by far the most abundant, followed by less abundant species *viz.*, *Coronosphaera mediterranea*, *Helicosphaera carteri*, *Calcidiscus leptoporus*, *Florisphaera profunda*, *Anoplosolenia braciensis*, *Calciosolenia murrayi* and *Oolithotus antillarum*. Minor species such as *Discosphaera tubifera*, *Syracosphaera pulchra*, *Umbellosphaera tenuis*, *Neosphaera coccolithomorpha*, *Algirosphaera oryza*, *Michaelsarsia adriaticus*, *Gladiolithus flabellatus* and *Rhabdosphaera clavigera* were also observed. Although 20 species were identified, the distribution patterns of only four dominant species along with moderately represented species (*Helicosphaera carteri*, *Calcidiscus leptoporus*, *Florisphaera profunda*, *Oolithotus antillarum*) are presented (figure 2a–b). In addition to the majority of isolated coccoliths, a few coccospheres comprising of *G. oceanica*, *E. huxleyi*, *G. flabellatus*, *A. oryza*, *F. profunda*, *C. leptoporus* were also observed in association with a few diatoms and silicoflagellates.

Total fluxes of coccolithophores displayed seasonality with highest fluxes ( $50.6 \times 10^6\ \text{m}^{-2}\text{d}^{-1}$ ) occurring during NE monsoon (7 January–3 March 1994) and relatively high fluxes

Table 1. Temporal distribution of coccolith and coccosphere (in parentheses) fluxes ( $\times 10^6 \text{ m}^{-2} \text{ d}^{-1}$ ) recorded between 18 October 1993 and 12 August 1994.

Species	Sampling period											
	18/10/93– 14/11/93	14/11/93– 11/12/93	11/12/93– 7/01/94	7/01/94– 3/02/94	3/02/94– 2/03/94	2/03/94– 29/03/94	29/03/94– 25/04/94	25/04/94– 22/05/94	22/05/94– 19/06/94	19/06/94– 16/07/94	16/07/94– 12/08/94	
<i>Anoplosolenia brasiliensis</i>	0.33	0.80	–	0.77	0.58	0.52	0.25	0.25	0.11	0.66	–	
<i>Algirosphaera oryza</i>	–	–	–	–	–	–	–	0.11	–	0.80 (0.39)	–	
<i>Calcidiscus leptoporus</i>	2.84	2.10	2.24 (0.13)	1.27	1.16	1.96	1.60	1.85	0.61	0.39	–	
<i>Coronosphaera mediterranea</i>	0.11	0.39	0.52	0.94	0.58	0.52	1.60	0.99	2.10	0.66	–	
<i>Calciosolenia murrayi</i>	0.11	0.28	–	0.47	0.47	0.39	0.11	0.11	0.50	0.14	–	
<i>Discosphaera tubifera</i>	–	–	–	0.17	–	–	0.11	0.25	0.25	0.28	–	
<i>Emiliania huatleyi</i>	10.18	13.50	5.52 (0.13)	12.28 (0.16)	5.22	7.62	5.16	3.06	7.84 (0.49)	6.02 (0.39)	–	
<i>Florisphaera profunda</i>	0.22	0.52	0.28	0.77	0.22	0.14	0.75	0.25	0.75 (0.12)	0.28	–	
<i>Gephyrocapsa oceanica</i>	17.75	15.76 (0.26)	15.76 (0.13)	25.28	12.09	14.68 (0.26)	14.41	15.40	16.61 (0.12)	22.52	–	
<i>Gladiolithus flabellatus</i>	–	–	–	–	–	–	–	–	0.36 (0.12)	–	–	
<i>Helicosphaera carteri</i>	0.44	0.80	0.39	0.94	0.36	–	0.25	0.50	0.50	0.28	–	
<i>Michaelsarsia adriaticus</i>	–	–	–	–	–	–	–	0.86	–	–	–	
<i>Neosphaera coccolithomorpha</i>	–	–	–	–	0.11	–	–	–	–	–	–	
<i>Oolithothus antillarum</i>	0.33	2.48	0.91	0.47	1.16	2.48	3.20	0.99	1.71	1.57	–	
<i>Rhabdosphaera clavigera</i>	–	–	–	0.17	–	0.14	0.00	0.25	0.11	0.39	–	
<i>Syracosphaera pulchra</i>	0.22	–	–	0.30	0.22	–	0.00	0.25	0.25	–	–	
<i>Umbellosphaera irregularis</i>	1.44	2.90	1.57	2.81	1.85	2.62	2.84	8.61	7.98	3.92	–	
<i>Umbellosphaera sibogae</i>	2.95	7.09	6.71	3.45	4.39	4.47	4.53	3.81	2.35	4.06	–	
<i>Umbellosphaera tenuis</i>	–	0.14	–	0.17	0.11	0.00	0.11	0.00	0.75	0.28	–	

Table 2. Taxonomic list of the coccolithophore species recorded in the sediment trap at 1018 m water depth at the sediment trap location in the central Arabian Sea.

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1.	<i>Anoplosolenia brasiliensis</i> (Lohmann 1919) Deflandre 1952.
2.	<i>Algirosphaera oryza</i> Schlauder 1954.
3.	<i>Calcidiscus leptoporus</i> (Murray and Blackman 1898) Loeblich and Tappan 1978.
4.	<i>Coronosphaera mediterranea</i> (Lohmann 1902) Gaarder and Heimdal 1977.
5.	<i>Calciosolenia murrayi</i> Gran 1912.
6.	<i>Discosphaera tubifera</i> (Murray and Blackman 1898) Ostenfeld 1900.
7.	<i>Emiliania huxleyi</i> (Lohmann 1902) Hay and Mohler 1967.
8.	<i>Florisphaera profunda</i> Okada and Honjo 1973.
9.	<i>Gephyrocapsa oceanica</i> Kamptner 1943.
10.	<i>Gladiolithus flabellatus</i> (Halldal and Markali 1955) Jordan and Chamberlain 1993.
11.	<i>Helicosphaera carteri</i> (Wallich 1877) Kamptner 1954.
12.	<i>Michaelsarsia adriaticus</i> (Schiller 1914) Manton <i>et al</i> 1984.
13.	<i>Neosphaera coccolithomorpha</i> Lecal – Schlauder 1950.
14.	<i>Oolithotus antillarum</i> (Cohen 1964) Reinhardt in Cohen and Reinhardt 1968.
15.	<i>Rhabdosphaera clavigera</i> Murray and Blackman 1989.
16.	<i>Syracosphaera pulchra</i> Lohmann 1902.
17.	<i>Umbellosphaera irregularis</i> Paasche (1950).
18.	<i>Umbellosphaera sibogae</i> var. <i>foliosa</i> (Kamptner 1963) Okada and McIntyre 1977.
19.	<i>Umbellosphaera tenuis</i> (Kamptner 1937) Paasche.

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( $43.6 \times 10^6 \text{ m}^{-2} \text{ d}^{-1}$ ) during early SW monsoon (22 May–19 June 1994) (figure 2a).

Among the dominant species, *G. oceanica* showed higher flux values ( $12.1\text{--}25.3 \times 10^6 \text{ m}^{-2} \text{ d}^{-1}$ ) than *E. huxleyi* ( $3.1\text{--}13.5 \times 10^6 \text{ m}^{-2} \text{ d}^{-1}$ ). The fluxes of *U. irregularis* ranged from  $1.4\text{--}8.6 \times 10^6 \text{ m}^{-2} \text{ d}^{-1}$  with a marginal decrease during SW monsoon (figure 2a and table 1). *U. sibogae* ranged from  $2.4\text{--}7.1 \times 10^6 \text{ m}^{-2} \text{ d}^{-1}$  showing higher fluxes during NE monsoon compared to SW monsoon. Fluxes of *F. profunda* ranged from  $0.1\text{--}0.8 \times 10^6 \text{ m}^{-2} \text{ d}^{-1}$  while *C. leptoporus* ranged from  $0.4\text{--}2.8 \times 10^6 \text{ m}^{-2} \text{ d}^{-1}$  (figure 2b and table 1).

## 5. Discussion

An examination of mean monthly wind stress curl fields and the associated Ekman pumping velocity at the base of the Ekman layer computed from the Florida State University pseudo wind stress data for the 1993–97 period showed the distinct SW–NE orientation of the ‘zero’ contours of wind stress curl and Ekman pumping velocity from the Somali coast to the Indian coast over the central Arabian Sea (figures are not shown here). The analysis further showed that during October–March (NE monsoon), downwelling (upwelling) occurs to the north (south) of these ‘zero’ contours covering the northwestern, northern and central Arabian Sea, whereas during June–September (SW monsoon) upwelling (downwelling) occurs to the north (south) of these ‘zero’ contours aligned with the

axis of Findlater Jet. Ekman pumping off Somalia and in the central Arabian Sea forces a strong Summer Monsoon Current (SMC) across western Arabian Sea and central Arabian Sea during SW monsoon (Shankar *et al* 2002). The Ekman drift (in a thin upper oceanic layer) and the net surface flow (Ekman drift + geostrophic flow) are towards central and western Arabian Sea during NE monsoon and towards southeast in the central Arabian Sea during SW monsoon. Ekman drift and net surface flow would play a major role in the advection of nutrients from northern Arabian Sea (including the Pakistan coast) to central Arabian Sea during NE monsoon and from the Oman coast to central Arabian Sea during SW monsoon (Morrison *et al* 1998). Thus, it is surmised that the advection of nutrients towards the central Arabian Sea both during SW and NE monsoons would trigger primary productivity in this region and result in the variability of coccolithophores as recorded in the sediment trap samples at greater depth. Maps of satellite derived Sea Surface Temperature (SST) and blended from buoys (moored and drifting) data, for the study period (November 1993, January 1994, May 1994 and July 1994) (Reynolds and Smith 1994) showed intense winter cooling in the northern and western Arabian Sea and the spread of low temperature waters towards central Arabian Sea (closer to the trap location) by January 1994, intense warming in May in the central Arabian Sea, and relatively warmer temperatures south of the Findlater Jet in the central Arabian Sea in July (figure 3a–d). The Simple Ocean Data Assimilation (SODA) Parallel Ocean

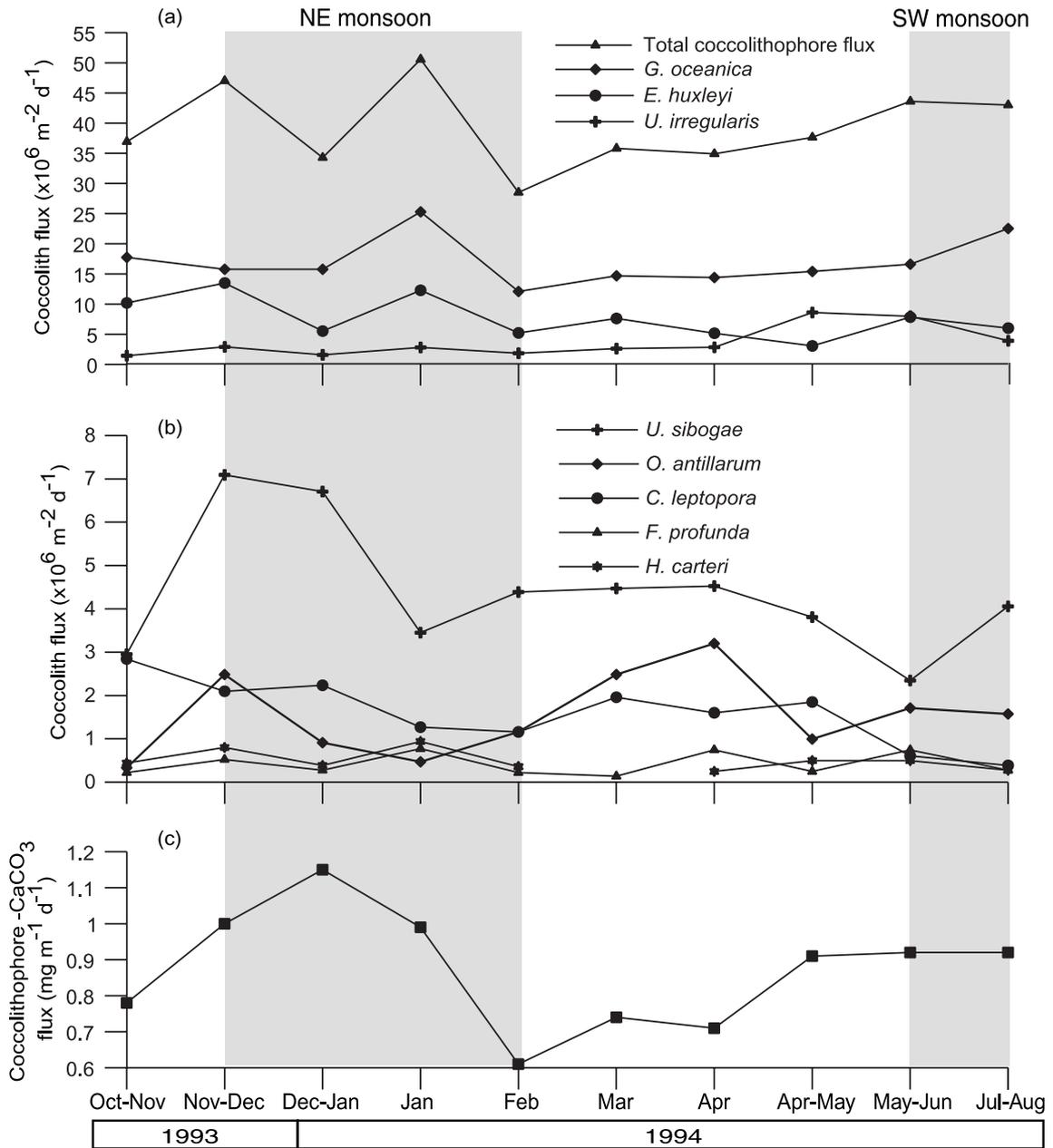


Figure 2. Temporal variation of (a & b) total coccolithophore fluxes and fluxes of major individual species of coccoliths ( $\times 10^6 \text{ m}^{-2} \text{ d}^{-1}$ ) and (c) total coccolithophore - CaCO<sub>3</sub> fluxes ( $\text{mg m}^{-2} \text{ d}^{-1}$ ) between 18 October 1993 and 12 August 1994.

Program (Carton *et al* 2000) model simulated surface currents during the study period (November 1993, January 1994, May 1994 and July 1994) are similar to ship drifts (figure 2a-b), but less noisy. It may be noted that the model as well as the ship-drifts do not capture some of the meso-scale eddies that are important during the winter monsoon (with reference to this study) as revealed by the altimeter derived sea surface height anomaly data (not shown here). The SODA\_POP surface currents suggested that the surface flow emanated from the eastern (western) Arabian Sea towards the central Arabian Sea (figure 4a-d)

in January (July), clearly under the influence of seasonal surface winds. The strong eastward flow from the Somalia and Oman coasts during July brings in the nutrient-rich upwelled waters towards central Arabian Sea. Thus, the impacts of seasonally varying wind forcing and the prevailing hydrographic conditions (affecting the nutrient variability and primary production through advection and upwelling/downwelling) in the central Arabian Sea have facilitated the interpretation of the temporal variability of various species of coccolithophores in the following paragraphs.

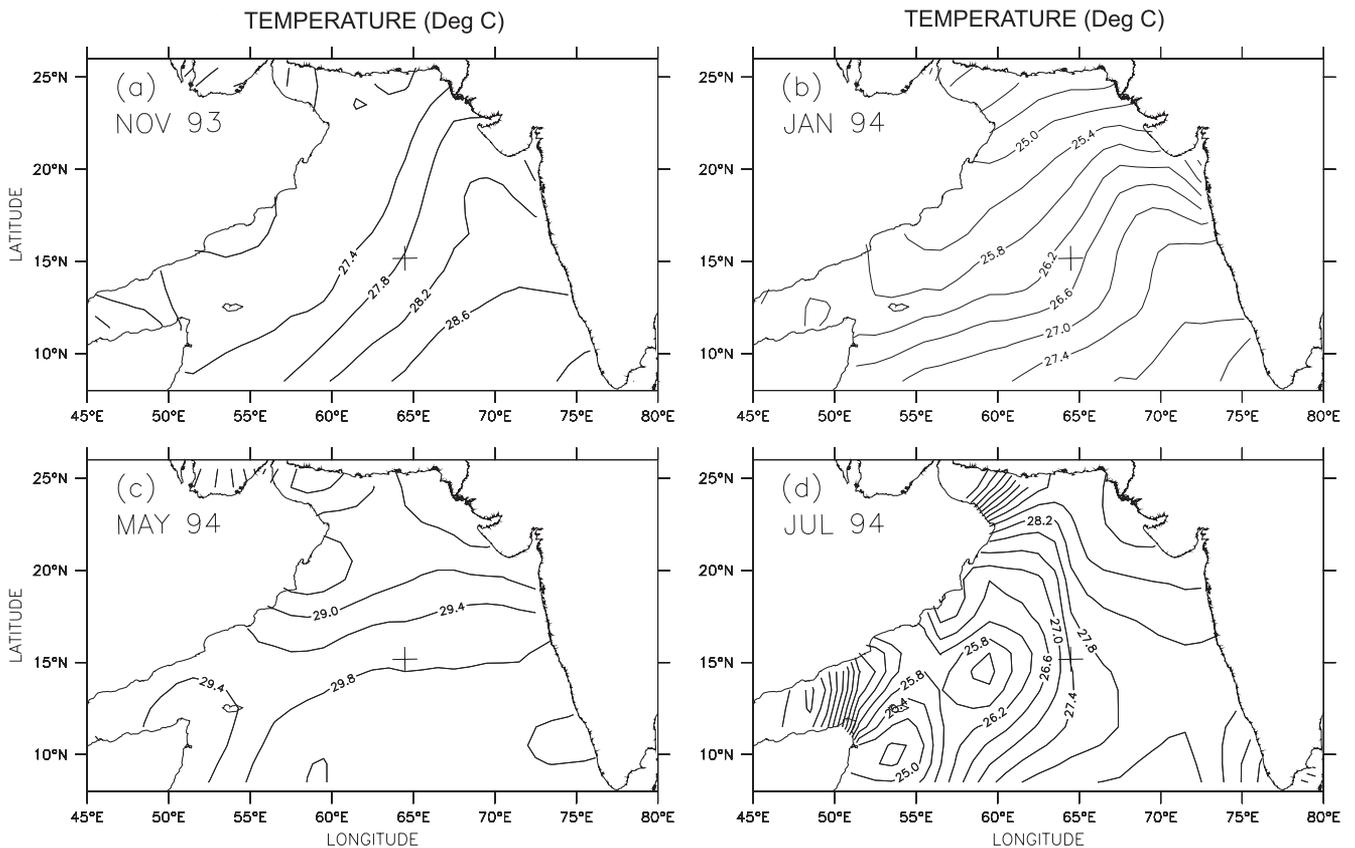


Figure 3. Variation of monthly mean satellite derived Sea Surface Temperature (SST) and blended from buoys (mooring and drifting) data in the Arabian Sea during (a) November 1993, (b) January 1994, (c) May 1994 and (d) July 1994. The sediment trap location is depicted by '+'.

The present observations showed highest coccolithophore fluxes ( $> 50 \times 10^6 \text{ m}^{-2} \text{ d}^{-1}$ ) in the central Arabian Sea during NE monsoon (figure 1 and table 1), which may be attributed to the advection of nutrients (via Ekman drift and surface currents, Shankar *et al* 2002; figures 4–5) from the northeast Arabian Sea and enhancement of primary production in the central Arabian Sea during NE monsoon. Broerse *et al* (2000) also reported higher fluxes of coccosphere ( $2.2 \times 10^6 \text{ m}^{-2} \text{ d}^{-1}$ ) and coccoliths ( $5.9 \times 10^8 \text{ m}^{-2} \text{ d}^{-1}$ ) during NE monsoon of 1993 than during SW monsoon of 1992 off Somalia. Andruliet *et al* (2000) reported higher fluxes off Pakistan shelf during NE monsoon and also at the beginning of SW monsoon. Curry *et al* (1992) also observed higher abundance of several foraminiferal species at the central Arabian Sea trap location more predominantly during NE monsoon rather than during SW monsoon.

Relatively lower coccolithophore fluxes (figure 2a and table 1) observed during spring intermonsoon corresponded to the oligotrophic conditions associated with the higher SST (figure 3c) and the lower nutrient concentrations due to thermal stratification in the upper ocean (Morrison *et al* 1998;

Prasanna Kumar *et al* 2001b; Prasanna Kumar and Narvekar 2005).

The overall observed fluxes of coccolithophores in the central Arabian Sea were higher during NE monsoon than SW monsoon, yet they were 2 to 5 times lower than those reported off Pakistan by Andruliet *et al* (2000) and off Somalia by Broerse *et al* (2000) which could be attributed to the intense upwelling conditions at these coasts during NE monsoon. The observed decrease of coccolithophore fluxes over a shorter duration during 11 December 1993–7 January 1994 (NE monsoon) was attributed to the effect of dissolution (as discussed in section 5.1) as evidenced by the presence of corroded coccoliths.

*G. oceanica* is predominantly a low-latitude species (Okada and McIntyre 1979) and shows a maximum flux during NE monsoon (7 January–3 February 1994) (figure 2a) due to availability of nutrients as mentioned above. Similarly, the lower fluxes seen during the fag end of NE monsoon (3 February–2 March 1994) could be either due to dissolution resulting from high productivity or due to the depletion of nutrients in the surface layer in association with the waning of winter conditions.

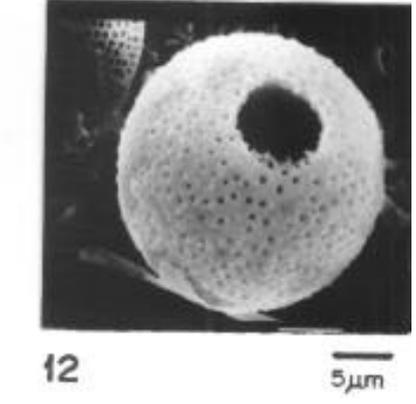
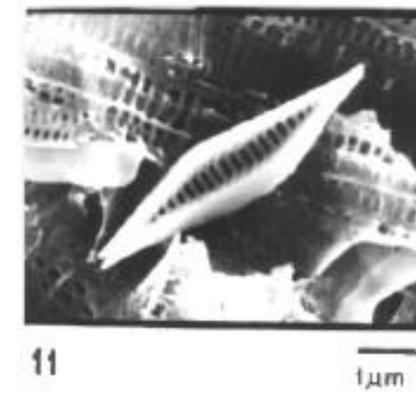
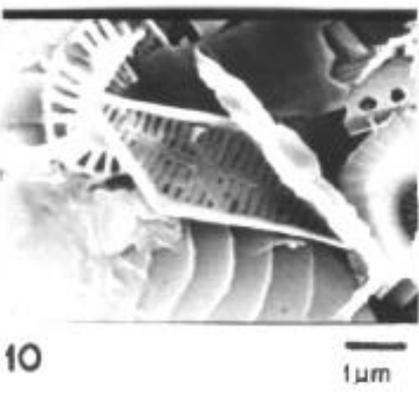
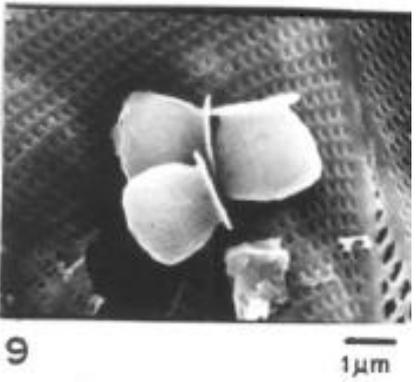
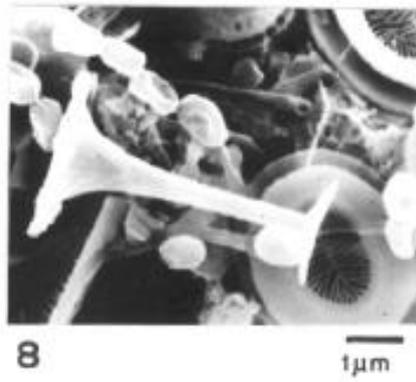
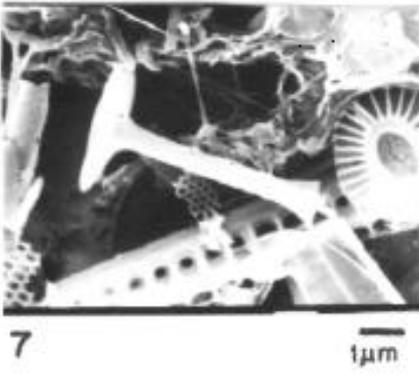
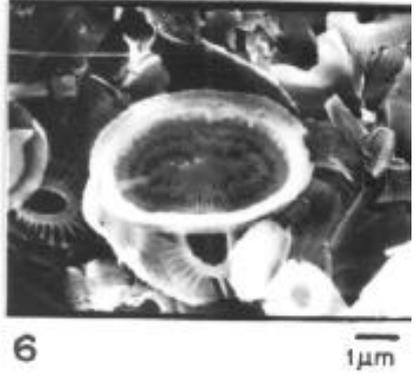
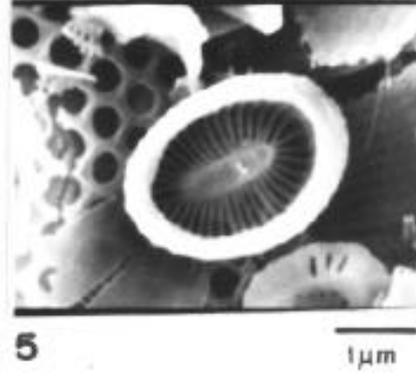
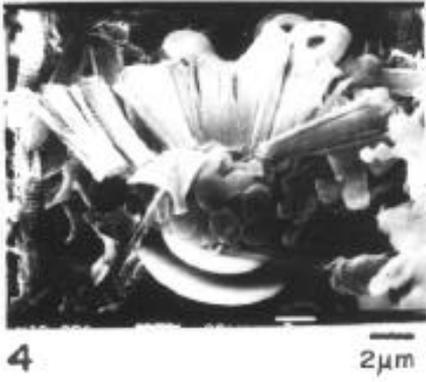
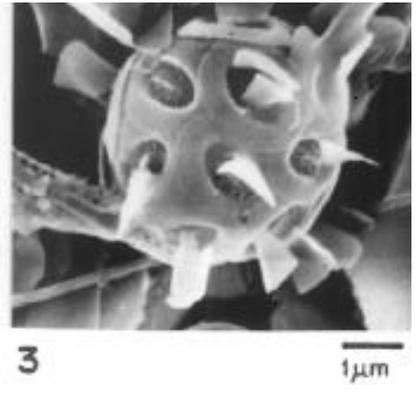
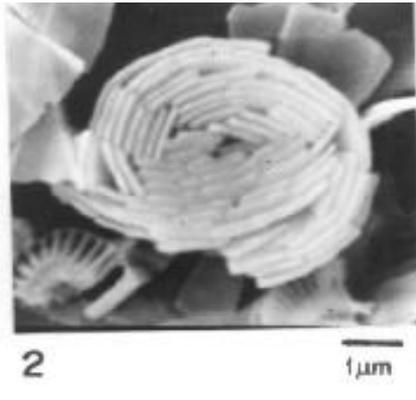
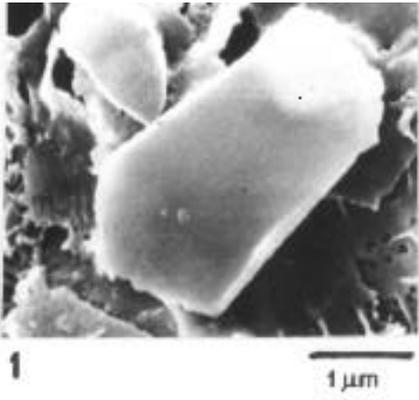


Plate 1.

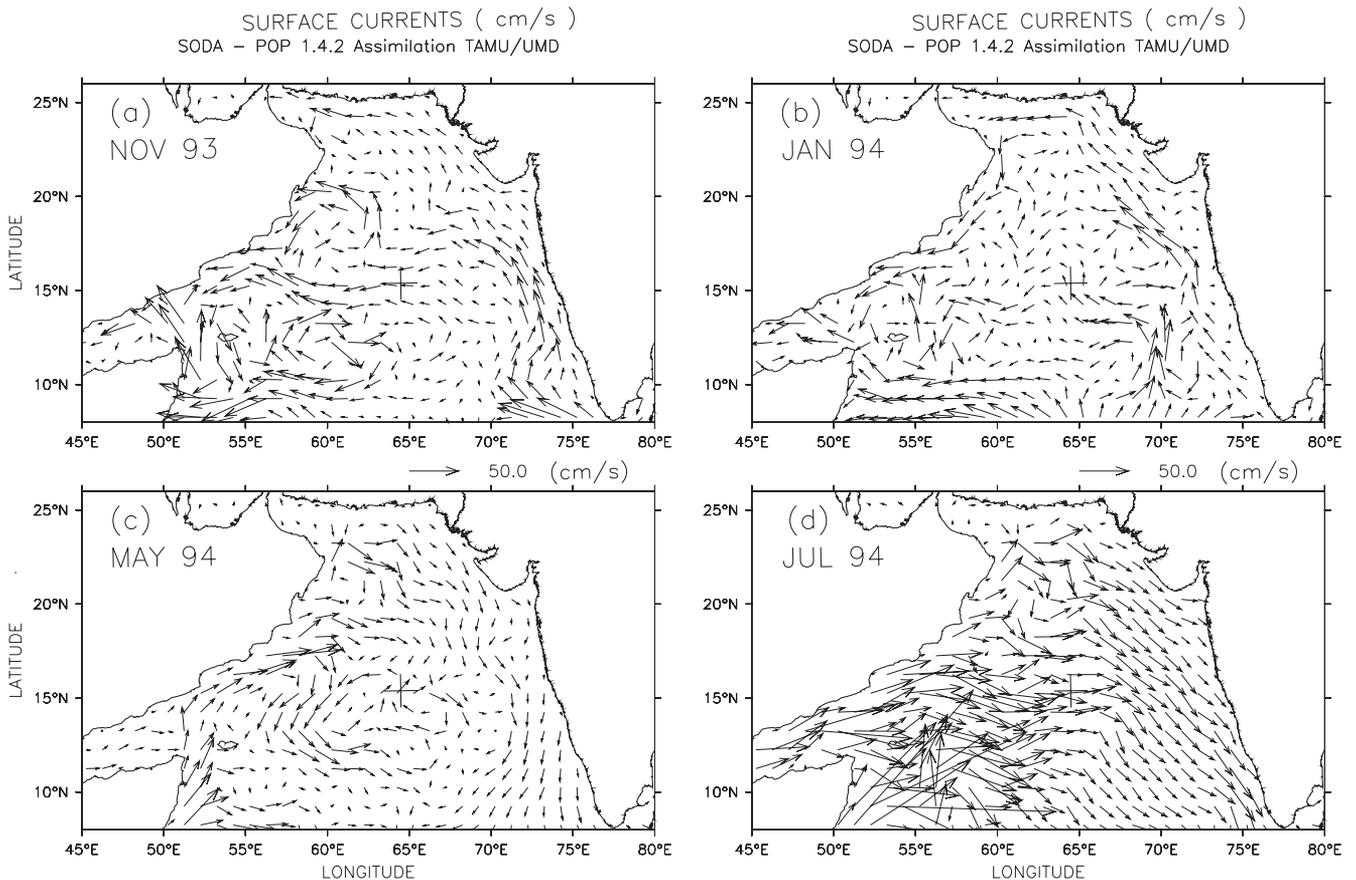


Figure 4. Variation of monthly mean simulated surface currents from Simple Ocean Data Assimilation and Parallel Ocean Program (SODA-POP) [<http://www.dsr.s.atmos.umd.edu/DATA/SODA-1.4.2>] during (a) November 1993, (b) January 1994, (c) May 1994 and (d) July 1994. For clarity alternate grid current vectors are shown. The sediment trap location is depicted by '+

Temporal variation of *G. oceanica* and the total coccolithophore flux displayed the same trends (figure 2a). *E. huxleyi* is a cosmopolitan species abundant in subtropical and tropical waters (2°–30°C) occurring over a wide range of salinities (16–45) (Okada and McIntyre 1977). *E. huxleyi* also showed a similar trend as that of total coccolithophore fluxes only from 18 October 1993 to 29 March 1994. The lower fluxes of this species during the early

SW monsoon (25 April–22 May 1994) might be due to shallow mixed layer depth associated with the thermal stratification of the upper ocean layer (Prasanna Kumar and Narvekar 2005). *G. oceanica* and *E. huxleyi* were widely reported to be the two common coccolith species in the world's ocean at low- to mid-latitudes (McIntyre and Bé 1967; Roth and Coulbourn 1982). These two species were reported as dominant from the northern Indian

#### Plate 1 caption

← Plate 1.

1. *Florisphaera profunda*, single coccolith (7 January–3 February 1994).
2. *Florisphaera profunda*, coccosphere (14 November–11 December 1993).
3. *Gephyrocapsa* ? sp. (Kleijne 1993) (16 July–12 August 1994).
4. *Gladiolithus flabellatus*, collapsed coccosphere (25 April–22 May 1994).
5. *Coronosphaera mediterranea*, distal view of coccolith (16 July–12 August 1994).
6. *Syracosphaera pulchra*, distal view of coccolith (16 July–12 August 1994).
7. *Rhabdosphaera clavigera*, isolated coccolith (16 July–12 August 1994).
8. *Discosphaera tubifera*, isolated coccolith (16 July–12 August 1994).
9. *Algirosphaera oryza*, isolated coccoliths (16 July–12 August 1994).
10. *Anoplosolenia brasiliensis*, distal view of ordinary coccolith (16 July–12 August 1994).
11. *Anoplosolenia brasiliensis*, distal view of apical coccolith (16 July–12 August 1994).
12. *Thoracosphaera heimii* (18 October–14 November 1993).

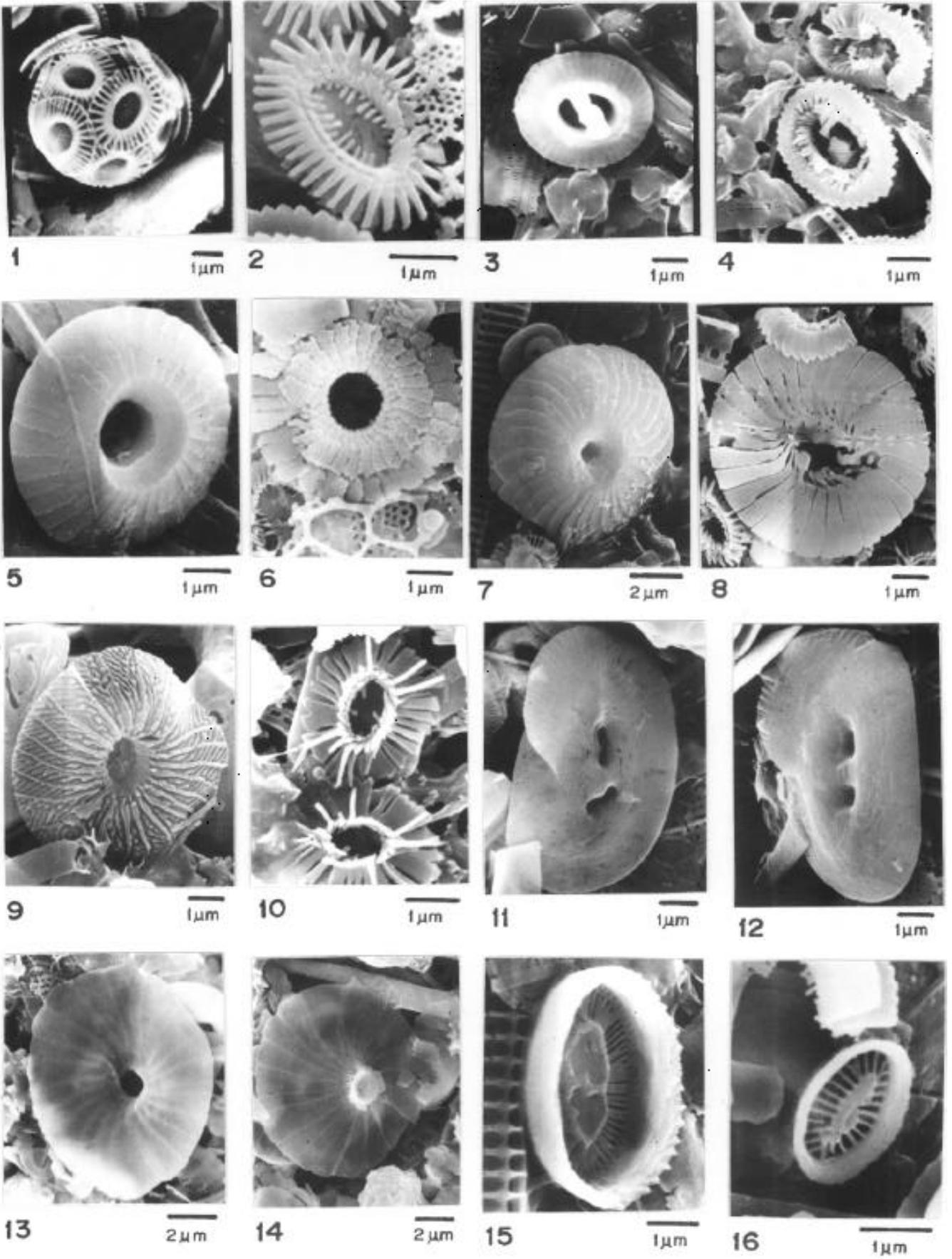


Plate 2.

Ocean by Kleijne (1993), Houghton and Guptha (1991) and Andruleit and Rogalla (2002) and are known to respond positively to nutrient enrichment by increasing their population both in the ocean as well as in culture. Zeltner (1998) reported maximum coccolithophore fluxes during upwelling relaxation period with *G. oceanica* and *E. huxleyi* as dominant species in the central Arabian Sea sediment trap location (CAST, 14°N, 64°E), which is in close agreement with the present work. Compared to *E. huxleyi*, *G. oceanica* is the dominant coccolithophore in the monsoon dominated marginal seas of the western Pacific and in open seas and on continental shelves of the northern and equatorial Indian Ocean (Kleijne 1993; Houghton and Guptha 1991). Broerse *et al* (2000) explained the dominance of *G. oceanica* over *E. huxleyi* by its preference for elevated nutrient levels. It was reported that *G. oceanica* and *E. huxleyi* do respond to nutrient enrichment in the equatorial and coastal upwelling areas and over continental shelves (Hulburt 1983; Mitchell-Innes and Winter 1987; Kleijne 1993; Houghton and Guptha 1991; Giraudeau *et al* 1993).

*F. profunda* is another ecologically important species which dwells in the lower photic zone of nutricline and plays a key role as an indicator of past productivity and upwelling (Ahagon *et al* 1993; Guptha *et al* 2005) and can also record a change in the nutricline (Molfino and McIntyre 1990). During the study period, fluxes of *F. profunda* varied over a smaller range between 0.1 and  $0.8 \times 10^6 \text{ m}^{-2} \text{ d}^{-1}$ , with an average flux of  $0.4 \times 10^6 \text{ m}^{-2} \text{ d}^{-1}$ . However, the fluxes of *F. profunda* showed a sharp increase (two times of its mean flux) on 3 occasions during January, April and June, when relatively higher nutrient

concentrations were available in the euphotic zone in the study area (Prasanna Kumar and Narvekar 2005).

*C. leptoporus* is one of the eurythermal species and widely distributed from equatorial to polar waters (McIntyre and Bé 1967). These authors reported higher abundance of *C. leptoporus* during NE monsoon compared to those during SW monsoon. In the present study, the maximum fluxes of this species were observed during 18 October–14 November 1993, NE monsoon of 1993 and spring intermonsoon of 1994. The lowest values recorded during 3 February–2 March 1994 might be attributed to dissolution. Ziveri *et al* (2000) also reported dissolution of this species from the sinking assemblages to the surface sediments in the north-eastern Atlantic.

*U. sibogae*, which prefers nutrient rich upwelled waters displayed higher fluxes during NE monsoon due to advection of these waters from the Pakistan coast towards the central Arabian Sea, which is in agreement with that reported by Broerse *et al* (2000). However, during SW monsoon, the fluxes of *U. sibogae* were less due to the downwelling process in the central Arabian Sea (south of the Findlater Jet axis).

*U. irregularis* is one of the most common species often reported from tropical waters and its distribution is limited to water temperatures between 21° and 28°C (McIntyre and Bé 1967). It acts as an indicator of oligotrophic conditions (Nishida 1979; Okada and McIntyre 1979; Kleijne 1993; Young 1994; Sprengel *et al* 2000). In the present study, *U. irregularis* showed a peak during spring intermonsoon (25 April–22 May 1994) due to prevailing oligotrophic conditions (higher SSTs (figure 3c) and nutrient poor waters, Prasanna Kumar

## Plate 2 caption

Plate 2.

1. *Emiliana huxleyi*, intact coccosphere (16 July–12 August 1994).
2. *Emiliana huxleyi*, distal view of coccolith showing dissolution (7 January–3 February 1994).
3. *Gephyrocapsa oceanica*, distal view of coccolith (16 July–12 August 1994).
4. *Gephyrocapsa oceanica*, coccoliths showing intense dissolution (7 January–3 February 1994).
5. *Umbellosphaera sibogae*, distal view of coccolith (14 November–11 December 1993).
6. *Umbellosphaera sibogae*, coccolith showing intense dissolution (7 January–3 February 1994).
7. *Calcidiscus leptoporus*, distal view of the coccolith (16 July–12 August 1994).
8. *Calcidiscus leptoporus*, coccolith showing intense dissolution (7 January–3 February 1994).
9. *Umbellosphaera tenuis*, distal view of the coccolith (2 March–29 March 1994).
10. *Umbellosphaera tenuis*, coccolith showing intense dissolution (7 January–3 February 1994).
11. *Helicosphaera carteri*, distal view of the coccolith (7 January–3 February 1994).
12. *Helicosphaera carteri*, coccolith showing signs of dissolution (16 July–12 August 1994).
13. *Umbellosphaera irregularis*, distal view of the coccolith (14 November–11 December 1993).
14. *Umbellosphaera irregularis*, proximal view of the coccolith (14 November–11 December 1993).
15. *Coronosphaera mediterranea*, distal view of the coccolith (7 January–3 February 1994).
16. *Michaelsarsia adriaticus*, single detached coccolith (16 July–12 August 1994).

and Narvekar 2005). This is followed by a decrease in its flux at the onset of SW monsoon with the onset of upwelling. Kleijne (1993) also reported that the *U. irregularis* showed negative correlation with upwelling conditions indicating its preference to oligotrophic conditions in the northern Indian Ocean. Furthermore, Kleijne (1993) also showed dominance of *U. irregularis* in warm oligotrophic conditions in the Gulf of Aden and the Red Sea during summer (June to July). Thus, the observed very low abundance of *U. irregularis* during NE monsoon (figure 2a) and its increase during spring intermonsoon supported its preference to oligotrophic waters in the central Arabian Sea.

### 5.1 Dissolution effect

Dissolution effect, as observed from the corroded coccolithophores, was prominent among the coccoliths such as *E. huxleyi*, *G. oceanica*, *C. leptopora* and *U. tenuis* only during NE monsoon (11 December 1993–3 March 1994). Interestingly, higher intensity of dissolution was noticed during 7 January–3 February 1994, when *E. huxleyi*, *G. oceanica*, *C. leptopora* and the total coccolithophore fluxes exhibited higher fluxes (figure 2a). As explained in the earlier paragraphs, the availability of nutrients and the associated enhancement in primary productivity might be the primary cause for the observed dissolution. It was generally believed that pH of the waters would decrease with the increased productivity, and would lead to dissolution of the coccolithophores. Supporting evidence could not be provided due to lack of observations in the study area. In view of the fact that the observed assemblages were a mixture of both corroded and intact coccolithophores, their slow settling velocities facilitate longer exposure to the corrosive waters leading to dissolution. The alternate source of the corroded coccolithophores might also be from the upwelling regions (Pakistan coast), from where the corroded coccolithophores advected towards the study area. Unlike the Bay of Bengal, the ballast theory of settling particles might not be pertinent to the central Arabian Sea, as it does not experience any terrigenous fluxes that would have otherwise helped for particle settling at a faster rate. Study of coccolithophore fluxes by Broerse *et al* (2000) shows that the preservation of coccoliths strongly depends on rapid transport for protection from corrosive water masses. They can resist dissolution by getting incorporated with fecal pellets and other oceanic macro-aggregates that are responsible for the rapid vertical transport to the sea floor. Samtleben and Bickert (1990) reported a similar finding in sediment trap samples from the subarctic Atlantic, the Lofoten basin. Andrueit

(2000) reported dissolution of *Coccolithus pelagicus*, while other species in the same samples did not show dissolution. From these observations he concluded that dissolution did not take place during or after entrapment of the coccolith assemblages, hence they must have originated from different source areas or have experienced different settling conditions. Owing to the differential dissolution of coccolithophores, a supply of corroded forms by advection cannot be ruled out, if they sink slowly. Milliman *et al* (1999) documented an increasing amount of evidence to suggest considerable dissolution of calcium carbonate well above the chemical lysocline and concludes that biologically mediated processes might be responsible for dissolution. In this study, we believe that the observed dissolution during NE monsoon was a biologically mediated phenomenon caused by enhanced productivity during this period. Recently, Guptha *et al* (2004) have also reported dissolution in the photic zone in the equatorial Indian Ocean.

### 5.2 Coccolithophore $\text{CaCO}_3$ fluxes in the central Arabian Sea

The coccolithophore  $\text{CaCO}_3$  flux was computed by multiplying the flux values of various species with their average coccolith weight (taken from Broerse *et al* 2000 and others). Thus, the estimated coccolithophore  $\text{CaCO}_3$  flux ranged from 0.6 to  $1.2 \text{ mg m}^{-2} \text{ d}^{-1}$ . High values of  $\text{CaCO}_3$  ( $1.2 \text{ mg m}^{-2} \text{ d}^{-1}$ ) were observed during NE monsoon (11 December 1993–7 January 1994), followed by a minimum value of  $0.6 \text{ mg m}^{-2} \text{ d}^{-1}$  during the fag end of NE monsoon (3 February–2 March 1994) and showed a marginal increase during early SW monsoon. Broerse *et al* (2000) reported  $8.1 \text{ mg m}^{-2} \text{ d}^{-1}$  as the mean yearly estimated coccolithophore- $\text{CaCO}_3$  flux (both loose coccolith and coccosphere) off Somalia in the western Arabian Sea. Furthermore, they also stated that the coccolithophore contribution to the total  $\text{CaCO}_3$  flux (calcareous microfossils) was higher during the early SW monsoon period.

## 6. Conclusions

This study of coccolithophore fluxes from the sediment trap samples in the central Arabian Sea, in general, showed enhanced fluxes during NE monsoon compared to SW monsoon. The advection of nutrient-rich waters from the upwelling regions in the northeast Arabian Sea to the central Arabian Sea by the prevailing Ekman drift and surface currents during NE monsoon and enhancement of primary productivity in the central Arabian Sea might be primary cause for the observed

higher fluxes during the winter season. Similarly, the relatively lower coccolithophore fluxes during SW monsoon were attributed to downwelling (or absence of upwelling) to the south of Findlater Jet axis where the sediment trap was located. *G. oceanica* was by far the most abundant during NE monsoon emphasizing the influence of northern Arabian Sea nutrient rich waters in winter season. *E. huxleyi* and *F. profunda* showed higher fluxes during NE monsoon and lower fluxes during SW monsoon suggesting the impact of the above-mentioned seasonally varying influence of physical forcing. *U. irregularis* showed higher fluxes during spring intermonsoon, when the availability of nutrients was low in the upper layer, confirming its preference for oligotrophic conditions. *C. leptoporus* and *U. sibogae* also showed seasonal variation with higher values during NE monsoon and low values during SW monsoon. On the contrary, *C. mediterranea* showed lower fluxes during NE monsoon and higher fluxes during spring intermonsoon, demonstrating their preference to low nutrients and higher temperature. This study clearly displays the variation of coccolithophore fluxes with the seasonally changing physical forcing over the central Arabian Sea.

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