

## Seasonal variation of pteropods from the Western Arabian Sea sediment trap

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### Abstract:

Sediment trap samples collected from the Western Arabian Sea yielded a rich assemblage of intact and non-living (opaque white) pteropod tests from a water depth of 919 m during January to September 1993. Nine species of pteropods were recorded, all (except one) displaying distinct seasonality in abundance, suggesting their response to changing hydrographical conditions influenced by the summer/winter monsoon cycle. Pteropod fluxes increased during the April--May peak of the summer monsoon, and reached maximum levels in the late phase of the southwest summer monsoon, probably due to the shallowing of the mixed layer depth. This shallowing of MLD coupled with enhanced nutrient availability provides ideal conditions for pteropod growth which is also reflected in corresponding fluctuations in the flux of the foraminifer *Globigerina bulloides*. Pteropod/planktic foraminifer ratios displayed marked seasonal variations, the values increasing during the warmer months of April and May when planktic foraminiferal fluxes declined. The variation in fluxes of calcium carbonate, organic carbon and biogenic opal show positive correlations with fluxes of pteropods and planktic foraminifera. Calcium carbonate followed by biogenic opal was the main contributor to the total particulate flux especially during the SW monsoon. In the study area pteropod flux variations follow the other flux patterns indicating that they too could be used as a potential tool for palaeoclimatic reconstruction of the immediate past.

## Introduction

Pteropods are marine gastropods adapted to pelagic life and common members of calcareous zooplankton communities in the upper ocean (Bé and Gilmer 1977; Almogi-Labin et al. 1998). Their tests are made of aragonite, which is susceptible to dissolution. Hence, their distribution is generally restricted to Quaternary sediments -- they are not found in older sediments, unlike their calcareous counterparts, foraminifers and coccoliths.

Pteropod tests are limited to shallow tropical and subtropical oceanic regimes such as the Arabian Sea (e.g. Herman and Rosenberg 1969; Singh and Rajarama 1997; Singh et al. 1998, 2001) and to marginal seas such as the Red Sea and the Mediterranean Sea (e.g. Almogi-Labin and Reiss 1977; Reiss et al. 1980; Almogi-Labin 1982, 1984; Almogi-Labin et al. 1986, 1991; Wang et al. 1997). Earlier studies on pteropods were initiated with the advent of pioneering oceanographic cruises such as that aboard the H.M.S. Challenger (Pelsener 1888), the Deutsche Tiefsee Expedition *Valdivia* (Meisenheimer 1905), the Percy Sladen Trust Expedition (Tesch 1910), the John Murray Expedition (Stubbings 1937), the *Dana* cruises (Tesch 1948), the *Umikata Maru* Expedition (Taki and Okutani 1962) and the International Indian Ocean Expedition (Sakthivel 1968, 1973). van der Spoel and colleagues (van der Spoel 1967, 1969, 1976, 1981; van der Spoel and Pafort-Van Iersel 1982) studied various forms and species of pteropods focussing on taxonomy. Bé and Gilmer (1977) provided a detailed zoogeographic and taxonomic review of pteropods from the world oceans.

Researchers have been using biogenic components of marine sediments as a tool for deciphering global sea-level changes and oceanographic and climatic history. Of these, foraminifera are the best studied. Still, the distribution of pteropods in marine sediments has also been investigated in detail. Berger (1978) drew up a global map indicating the depth limit of pteropod accumulation. The study showed a shoaling of the aragonite compensation depth (ACD) along the continental margins. Notably, western continental margins are more suitable for pteropod studies, as these gastropods constitute the major biotic component of the sediments (Herman and Rosenberg 1969; Singh and Rajarama

1997). For example, Herman and Rosenberg (1969) used pteropods for paleodepth determination along the northwestern continental shelf of India. Also, Late Quaternary sea-level fluctuations inferred from pteropod analyses have been reported for the southwestern shelf of India (Singh et al. 1998, 2001).

From the other regions of the world the usefulness of pteropods in palaeoceanography was demonstrated by Almogi-Labin (1982, 1984) and Almogi-Labin et al. (1986) from deep-sea cores and plankton tows in the Red Sea. Seasonal fluxes have been studied by Almogi-Labin et al. (1988) in the Sargasso Sea and a palaeoenvironmental reconstruction using pteropod data for the Holocene was reported by Almogi-Labin et al. (1991). Nevertheless, no attempt has been made to reconstruct palaeoceanographic / palaeoclimatic changes based on pteropod studies from the northern Indian Ocean.

This study aims at assessing the suitability of pteropods for the reconstruction of oceanographic/climatic change in the Western Arabian Sea, by comparing these data with better-established indicators such as foraminifers, organic carbon and calcium carbonate in sediment trap samples (Fig. 1). This approach based on sediment trap material has at least one advantage over "snap-shot" plankton net and sediment samples -- it allows us to investigate temporal distribution patterns of pteropods in relation to changing hydrography. The present work is the first of its kind to study temporal variations of pteropod assemblages from sediment traps in the Arabian Sea.

### **Oceanographic setting**

The winds over the Indian Ocean north of 10°S reverse their direction twice a year owing to the thermal contrast between the continental landmass and the ocean. They generally blow from the southwest during May--September (southwest summer monsoon) and from the northeast during November--February (northeast winter monsoon). March--April and October are months of transition with weaker winds. The winds are much stronger during the summer monsoon than during the winter monsoon. In response to the seasonal reversals of the annual winds, the tropical Indian Ocean undergoes large circulation transitions, seasonally reversing circulation (Warren 1966), strong annual and semi-

annual variations in sea surface temperature (SST), and upwelling/downwelling activities in the upper ocean.

### ***Monsoonal currents***

The monsoonal currents flow across the breadth of the northern Indian Ocean. The branches of the summer monsoon and the winter monsoon currents which flow around the Lakshadweep high and low in the south-eastern Arabian Sea (Bruce et al. 1994) link the circulations in the Arabian Sea and the Bay of Bengal.

#### *SW monsoon*

During this period, the alongshore winds and the positive wind stress curl at the north of the Findlaters jet axis (Hastenrath and Lamb 1979) result in coastal (McCreary et al. 1996) and open ocean upwelling off Oman (Smith and Bottero 1977; Brock et al. 1991) and Somalia (Fig. 2b). Lateral advection of upwelled waters from the Oman coast to the open ocean takes place in filaments (Morrison et al. 1998), and four such filaments have been reported for the study area in the Joint Global Ocean Flux Study Report no. 35 (JGOFS 2002; cf. closed square in Fig. 2). Similarly, water from the Somalia upwelling centre advects eastwards in the central Arabian Sea (Prasanna et al. 2001). Another feature is the clockwise-flowing Indian monsoon current (Tchernia 1980), the Somali Current -- its associated gyre in the Western Arabian Sea (Schott et al. 1990) -- and the North Equatorial Current which carries water from the south into the northern Arabian Sea. However, the influence of the Somali Current has been documented up to 8°N. To date, the region north of 8°N has not been studied in detail but climatological data (Conkright et al. 1994) show intrusion of these waters from the Equatorial Indian Ocean into the Western Arabian Sea up to 16°N.

Our preliminary observations suggest that, during the SW monsoon, the Somali Current extends to the trap site (16°N; cf. below), presumably resulting in plumes of nutrient-rich upwelled water at this locality. However, more detailed data are needed to confirm this (Fig. 2b).

## *NE monsoon*

During this period, the currents reverse their circulation pattern (Fig. 2a). The northeast monsoon current flows south of Sri Lanka and supplies water to the West Indian Coastal Current (Bruce et al. 1994). The Somali Current receives inflow in several branches from the east across the Arabian Sea, and then flows southwards to meet the northward-flowing East African Coastal Current at 2--4°S. These two flows supply the eastward-flowing South Equatorial Counter Current.

## **Material and methods**

Two PARFLUX Mark VI sediment traps (Honjo and Doherty 1988) were deployed (16°20'333N and 60°18'483E) off the coast of Oman along the climatological axis of the Findlater jet (Findlater 1969) at water depths of 919 and 4,018 m (Fig. 1).

The trap was sampled at intervals during the period 21 January to 24 September 1993. The initial sampling interval was 25 days (plus 1 day for the recovery/redeployment of the trap=26 days). From 22 July onwards, this was shortened to 12 days (plus 1 day for the recovery/redeployment of the trap=13 days) in order to ascertain any changes in fluxes under southwest monsoon conditions. For the present study samples from the trap deployed at a depth of 919 m has only been taken.

At the time of deployment, the sampling cups (13 per trap) were filled with filtered seawater collected at depth at the mooring site, and mercuric chloride ( $\text{HgCl}_2$ ,  $3.3 \text{ g l}^{-1}$ ) was added as a preservative to prevent the degradation of organic material.

After the recovery of the trap, the samples were wet-sieved onboard through a 1 mm mesh nylon sieve. The fraction <1 mm was split into 16 aliquots by using a rotary splitter onboard, filtered through 0.4  $\mu\text{m}$  Nucleopore filters, oven-dried at 40 °C and weighed. To calculate the particle flux, the dry weight of the trapped material smaller than 1 mm was divided by the duration of the sampling interval and used as data for total particulate flux.

For pteropod analysis, the dried samples were further sieved through a 63  $\mu\text{m}$  mesh sieve. All pteropod tests larger than 125  $\mu\text{m}$  were separated and mounted on slides for

examination under a stereo-zoom binocular microscope. Species were identified and classified following van der Spoel (1967), Bé and Gilmer (1977) and Almogi-Labin (1982).

For analysis of planktic foraminifera the fraction greater than 125 $\mu$ m was mounted on slides for quantification under a stereo-zoom binocular microscope. The total planktic foraminiferal flux as well as *Globigerina bulloides* flux were computed taking the number of foraminifers in the part of the split sample, divided by the duration of the sample and referred to as tests per m<sup>2</sup> per day.

One split of the sample was analysed for carbonate, organic carbon and opal. Carbonate was calculated by the conductivity change of a sodium hydroxide solution after injection of carbon dioxide released from the acid-treated sample (Wosthoff Carmograph 6). Organic carbon was computed as the difference between carbonate carbon and total carbon. Biogenic opal was estimated photometrically in a modified version of the method described by Mortlock and Froehlich (1989) and Koroleff (1983).

## **Results**

### ***Pteropod fluxes***

The pteropods encountered were mostly intact with opaque, white tests, indicating that the specimens collected in the sediment trap constitute the actual sinking assemblage, unlike living specimens which are transparent in colour. Both the pteropod flux and total particulate flux show similar distribution patterns. In addition, the intensity of these fluxes parallels that of the monsoons, especially in the late phase of the SW monsoon (Table 1). Note that the NE monsoon data are poorly represented because information for the period 16 February to 13 March 1993 is not available.

Nine species of pteropods were recorded at the trap site (Fig. 3).

- *Limacina inflata* was the species found most abundantly throughout the year, displaying two peaks -- one during March, associated with the northeast monsoon, the other during in the last week of July when its flux increased from 39 to 120 tests m<sup>-2</sup>

$2 \text{ day}^{-1}$ , the values increasing progressively at the end of August during the SW monsoon to reach  $303 \text{ tests m}^{-2} \text{ day}^{-1}$ .

- *Limnancina trochiformis* a tropical warm-water species, was second in abundance to *L. inflata* and showed a bimodal distribution pattern associated with the late periods of the NE and SW monsoons. During the last week of July, its flux increased from 3 to 36 tests  $\text{m}^{-2} \text{ day}^{-1}$  and reached a maximum of 73 tests  $\text{m}^{-2} \text{ day}^{-1}$  in the last week of August.

- *Creseis acicula* was observed throughout the year but at low frequency, except in the late half of August when its flux reached a maximum of 85 tests  $\text{m}^{-2} \text{ day}^{-1}$ , presumably associated with a shallower mixed layer depth (MLD).

- *Creseis virgula* occurred moderately throughout the year. Its peak abundance was during the first half of August during the southwest monsoon, consistent with its preference for cooler waters.

- *Limnancina bulimoides*, which prefers cooler waters and shallower MLDs showed a peak abundance of 25 tests  $\text{m}^{-2} \text{ day}^{-1}$  during March and the last week of August. This is consistent with its preference for the end phases of both the winter and summer monsoons.

- *Clio cuspidata*, a warm-water species, occurred only rarely at the trap location. Peak fluxes were associated with the SW monsoon during July and the first week of August.

- *Clio polita* a bathypelagic species rarely encountered in the upper few hundred metres of water (Bé and Gilmer 1977), was sparsely distributed throughout the year at the trap site, except for an increase in abundance from 4 to 51 tests  $\text{m}^{-2} \text{ day}^{-1}$  during the late phase of the SW monsoon month of August. This is the first report of *C. polita* from the Arabian Sea.

- *Clio pyramidata* a species preferring the intermonsoon period of March, occurred in low numbers at the trap location.
- *Diacria quadridentata* was a very rare member of the pteropod assemblage.

*Planktic foraminifer, opal, organic carbon and calcium carbonate fluxes*

At the sediment trap in the Western Arabian Sea, fluxes of planktic foraminifers generally dominated over those of pteropods during the ca. 8-month study period in 1993 (Table 1). However, pteropods were more abundant during the intermonsoon period. Thus, during the NE--SW intermonsoon months of April--May, pteropod fluxes exceeded foraminiferal fluxes by factors of ca. 1.3--1.7 (Table 1, Fig. 4).

Increases in both foraminifer and pteropod fluxes coincided with the occurrence of the SW monsoon (Table 1, Fig. 4, and see above). A bimodal distribution pattern showed the foraminifer flux peaking in mid-August and the pteropod flux at the end of August--early September. The former was largely due to the occurrence of a *Globigerina bulloides* bloom earlier during the SW monsoon (Fig. 3).

Temporal variations in fluxes of calcium carbonate, organic carbon and opal show positive correlations with fluxes of pteropods and planktic foraminifers, the values increasing between the last week of June and mid-August (Fig. 4). During this time period, bimodal distributions were recorded for these variables, with increased fluxes of organic carbon, calcium carbonate and planktic foraminifers during the SW monsoon and in the late phase of the SW monsoon, increased fluxes of opal and pteropods.

At the trap site in the Arabian Sea, calcium carbonate was the main contributor to total particulate flux, followed by organic carbon, especially during the SW monsoon (Fig. 4). High fluxes of calcium carbonate in the early phase of the SW monsoon were associated with peak fluxes of organic carbon. In contrast to the May--June phase of the SW monsoon, opal flux (biogenic silica) dominated during the late phase of the SW monsoon in August--September (Fig. 4).



## Discussion

The data presented above for the Western Arabian Sea trap revealed that pteropod fluxes increased during the SW summer monsoon, particularly during the late phase at the end of August. Thus, dominant species such as *L. inflata*, *L. trochiformis* and *C. acicula* were all observed at the end of August. Other species, such as *D. quadridentata*, *C. pyramidata* and *C. cuspidata*, show deviations from this pattern. *D. quadridentata* showed a preference for the NE winter monsoon -- it did not respond to SW monsoon conditions when cool nutrient-rich waters presumably reached the trap site. This suggests that this species could be used as an indicator of winter stratification of waters in this study area. Note that, in the present case, this could not be fully confirmed because of the absence of data for the month of February. By contrast, *C. pyramidata*, considered to be a characteristic subtropical species, did not show any particular preference for either the one or the other monsoon period. Evidently, this species is of limited use for effectively reconstructing past oceanographic conditions. Interestingly, *C. cuspidata*, a tropical species, peaked in abundance in July—August, during the SW monsoon period, suggesting the overriding importance of nutrient enrichment in promoting the growth of this species.

The increase in pteropod abundance during the late half of the SW monsoon was reflected in corresponding patterns with other well-established palaeoclimatic indicators, such as organic carbon, opal, calcium carbonate, *G. bulloides* and total foraminiferal flux. Similar results were reported by Conan and Brummer (2000) from the Western Arabian Sea Trap off Somalia. Our observations indicate a higher abundance of pteropods (certain species) in the end phase of the SW monsoon when the MLD is shallower, compared to the earlier phase (Rao et al. 1989; Babu et al. 2004). This finding is validated by the data for the well-established upwelling indicator, *G. bulloides*, which show a similar variation. *G. bulloides* is a cold-tolerant species and flourish in nutrient-rich water, such as that of upwelling regions. During the late phase of the SW monsoon, nutrient-rich cold water from the Somalia and Oman upwelling regions presumably reached the trap site, promoting the 1993 *G. bulloides* bloom documented in the present study.

### ***Total particulate flux***

During the SW monsoon, a low-level Findlater jet blows due to extreme atmospheric conditions (Findlater 1969), triggering upwelling near the coasts of Oman and Somalia. In addition, the area north of the Findlater jet is subjected to positive wind stress curl (Hastenrath and Lamb 1979), responsible for upwelling (coastal and open ocean), variation in MLD (Rao et al. 1989; Babu et al. 2004) and subsequent injection of nutrients into the euphotic zone, leading to high particle fluxes (Nair et al. 1989). For the present sampling period in 1993, published SST data indicate that upwelling was initiated during the last week of May along the Somali coast, and was fully developed by mid-June at the trap location. Thus, there was a drop in SST during mid-June centred off the Oman coast and a rather sharp decrease in SST was documented during July (Reynolds and Smith 1995). This drop in SST and the associated increased particle flux pattern are characteristic for the SW monsoon. Although data for the period 16 February-13 March are not available for 1993, in an earlier study Nair et al. (1989) reported a bimodal distribution pattern of particle flux for the study area, i.e. during the NE monsoon and the SW monsoon for the present trap site. Thus, our data confirm the intimate link between particle flux and monsoonal conditions for the Western Arabian Sea.

US JGOFS studies (JGOFS 2002) revealed that during the early phase of the SW monsoon, inorganic nitrate/silicate ratios increase in the Arabian Sea (~1.6, compared to a "normal" ratio of 1), favouring carbonate-producing zooplankton and phytoplankton growth. Moreover, data from a mooring system deployed in the vicinity of the present trap locality during the US JGOFS field experiment, i.e. the Arabian Sea Central Mooring (ASCM), revealed that the initial mixed layer deepened and subsequently became shallower due to the advection of upwelled waters (Dickey et al. 1998; Fischer 2000; Babu et al. 2004). Therefore, the higher fluxes of calcium carbonate and the peak flux of organic carbon documented in the present study in the early phase of the SW monsoon can be attributed to a deepening of the mixed layer and subsequent injection of nutrients, mainly nitrates, into the euphotic zone (Nair et al. 1989). Haake et al. (1993) reported silicate concentrations in the water column increasing more than those nitrate and

phosphate suggesting that the initial mixed layer deepening is too weak to channel silicates into the euphotic zone, which would explain the increased nitrate/silicate ratios promoting carbonate production.

Biogenic silica is contributed mainly by the diatom species *Rhizosolenia* and *Nitzschia*, which are well-known indicators of upwelling. In the study region, increased biogenic silica production is attributed to the shallowing of the mixed layer due to the lateral advection of silica-rich water from coastal upwelling zones in the vicinity of the trap site. Prasanna et al. (2001) estimated the advection velocity to be  $0.28 \text{ m s}^{-1}$  and based on this velocity and the location of the trap 900 km from the Somali coast, the advected water would have reached the trap site in about 40 days. This would explain our observations of increased opal flux during the last week of July, and the peak in mid-August approx. 40 days after the SST decrease in July 1993 (cf. above; Reynolds and Smith 1995), consistent with our interpretation that upwelling was initiated in the last week of May and became fully developed in mid-June. On the other hand, carbonate and organic carbon contents generally decreased in the samples, probably due to the shallowing of the MLD as silica-rich waters from the Somalia upwelling centre reach the trap site. This finding is consistent with the general decrease in organic carbon flux with distance from the coast, since the offshore-propagating upwelled water decreases the MLD (Lee et al. 1998).

### ***Preferential growth of planktic foraminifer and pteropod species***

Biogenic carbonate is constituted largely by planktic foraminifers and coccolithophores. At certain depths and during certain periods of the year, however, pteropods dominate or occur in equal proportion as that of foraminifers. Increase in foraminifer and pteropod fluxes recorded in the present study, coinciding with the SW monsoon and showing a bimodal distribution pattern (mid-August and end of August respectively; cf. above) may be due to variations in the MLD induced by positive wind stress curl (Rao et al. 1989; Babu et al. 2004), promoting the growth of specific assemblages of microorganisms. Our data suggest that planktic foraminifers prefer deeper mixed layers, as they dominated in mid-August whereas, in the late phase of the SW monsoon, pteropods increased in

abundance when the MLD presumably shallowed. This shallowing of the mixed layer depth at the end of August is consistent with the increase in abundance of *G. bulloides*. However, carbonate fluxes decreased as the water was replaced by silica rich waters via advection from the Somalia upwelling centre.

## Conclusions

The pteropod tests recovered in the Western Arabian Sea sediment trap were of intact, white, opaque appearance, indicating that they belonged to sinking assemblages. White test walls indicate the initial stage of diagenesis. Furthermore, the good preservation of these pteropods suggests that the ACD lies very close to the trap depth (919 m). Seeing that the CCD lies at depths exceeding 4,000 m in the northern Indian Ocean, this implies that in this region variations in pteropod/planktic foraminifer ratios indicate the degree of preservation and/or the level of production of pteropods.

During the NE--SW intermonsoon period (March--May), total particulate fluxes increased, although not as much as in the SW monsoon period. SST increases during this period which shallows the MLD. This shallowing of the mixed layer, coupled with increased nutrient availability, would provide ideal conditions for pteropod growth. This is well reflected in variations in pteropod/planktic foraminifer ratios. Hence, in this study it can be concluded that the increase in pteropod/planktic foraminifer ratios is not an indication of improved preservation but rather of increased abundance of pteropods. This interpretation is consistent with the nature of the pteropod assemblages recovered in the trap. Since the pteropod variations were similar to other flux patterns in the study area, this can be used as a potential tool in palaeoclimatic reconstruction. Furthermore, it can be used to study seasonal variations in MLDs, as it shows a bimodal distribution pattern which can be explained in terms of MLD variation, which has palaeoceanographic implications.

Some pteropod species, such as *Limancina inflata*, *Limancina trochiformis* and *Limancina bullimoides*, showed characteristics similar to those of *Globigerina bulloides*, an established upwelling indicator. Therefore, these pteropods could serve as indicators of upwelling events.

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**Table 1** Collection periods in 1993, total particulate fluxes (dry weight basis), pteropod fluxes (125--1,000  $\mu\text{m}$  size fraction), planktic foraminifer fluxes and pteropod/planktic foraminifer ratios for the PARFLUX VI sediment trap deployed at 919 m in the Western Arabian Sea (*n.d.* no data)

Collection period, 1993	Total particulate flux	Pteropod flux	Planktic foraminifer flux	Pteropod/ planktic foraminifer ratio
	( $\text{mg m}^{-2} \text{ day}^{-1}$ )	(tests $\text{m}^{-2} \text{ day}^{-1}$ )	(tests $\text{m}^{-2} \text{ day}^{-1}$ )	
21 Jan.--15 Feb.	29.9	44	51	0.86
16 Feb.--13 Mar.	n.d.	n.d.	n.d.	n.d.
14 Mar.--8 Apr.	71.76	408	433	0.94
9 Apr.--4 May	91.78	84	66	1.27
5 May--30 May	99.54	117	69	1.69
31 May--25 Jun.	92.09	48	86	0.55
26 Jun.--21 Jul.	100.02	72	90	0.80
22 Jul.--3 Aug.	240.31	350	777	0.45
4 Aug.--16 Aug.	783.62	672	2,235	0.30
17 Aug.--29 Aug.	400.95	490	872	0.56
30 Aug.--11 Sep.	628.19	834	1,273	0.65
12 Sep.--24 Sep.	391.41	128	773	0.16

## CAPTION TO FIGURES

**Fig. 1** Sediment trap location in the Western Arabian Sea (*WAST*)

**Fig. 2a, b** Surface current vectors derived from ship drifts in the Arabian Sea during **a** January (NE winter monsoon) and **b** July (SW summer monsoon; after Mariano et al. 1995). The sediment trap location is depicted as a *closed square* in the Western Arabian Sea

**Fig. 3** Seasonal variations in total pteropod flux, individual pteropod species abundance, and abundance of the foraminifer *Globigerina bulloides*

**Fig. 4** Seasonal variations in total pteropod flux, total planktic foraminifer flux, calcium carbonate flux, organic carbon flux, opal flux and pteropod/planktic foraminifer ratios



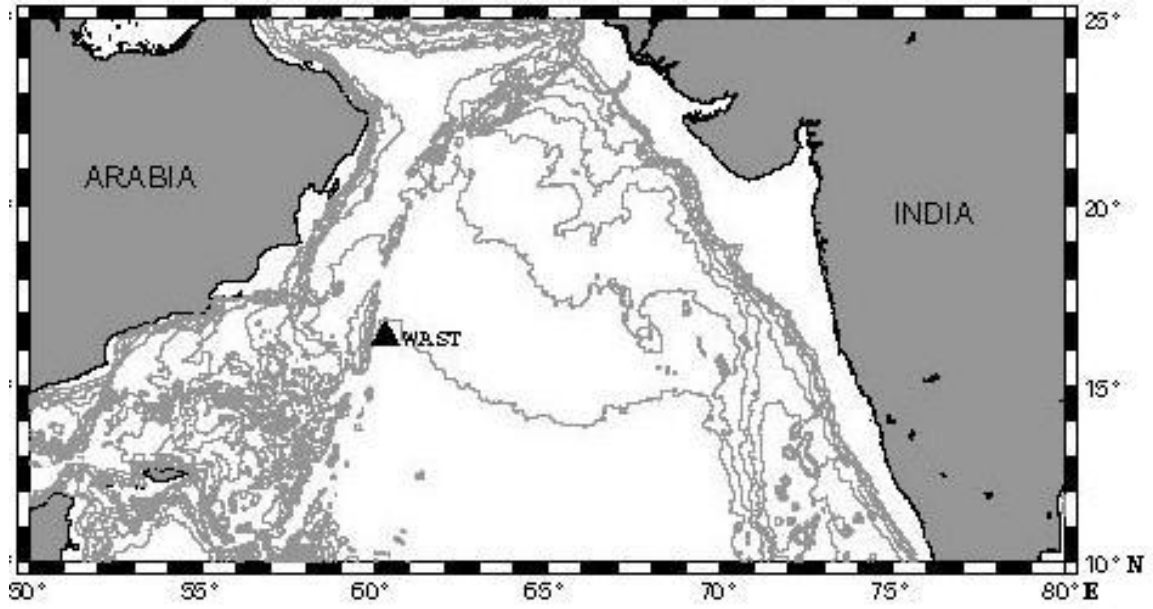
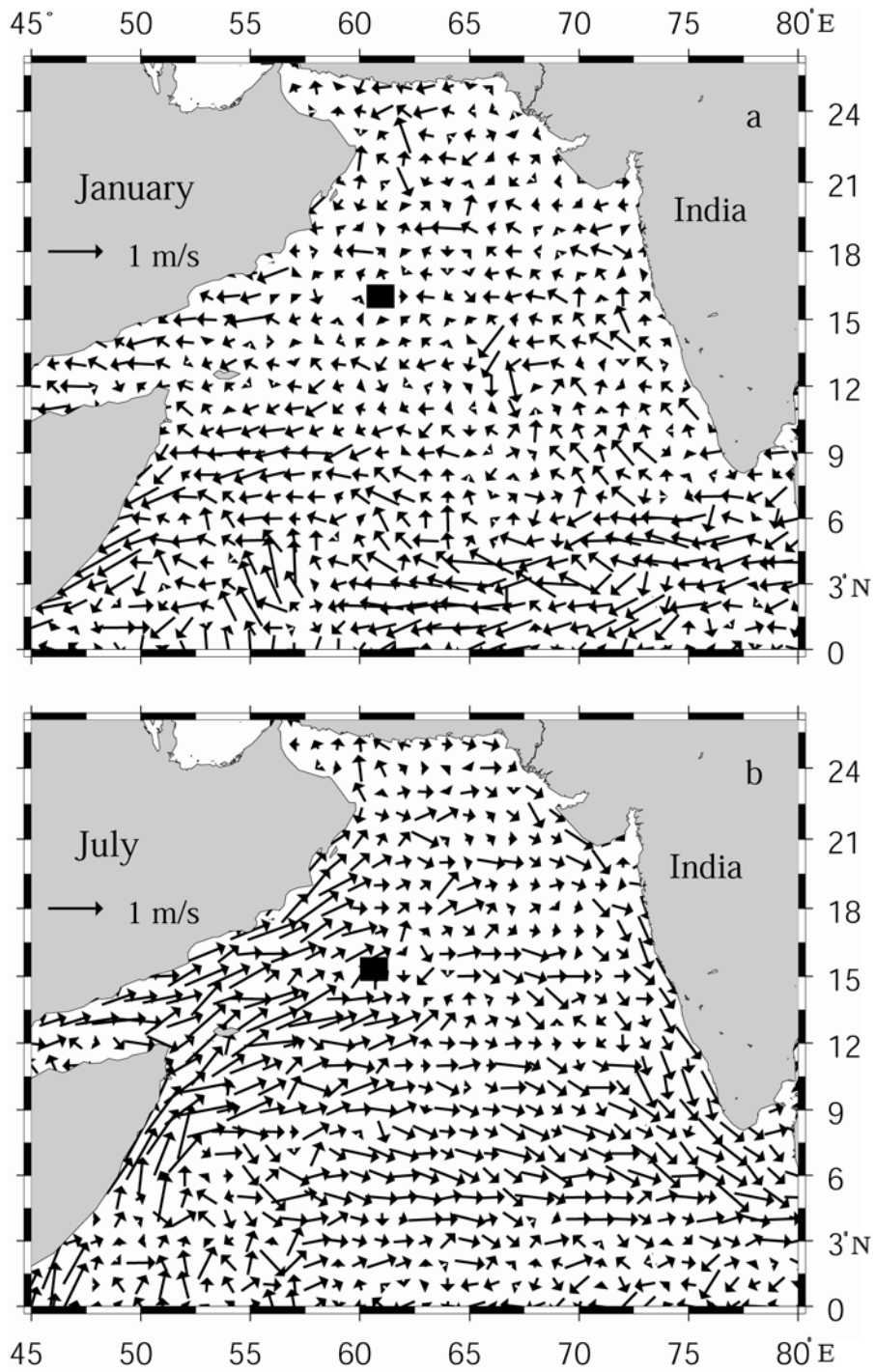
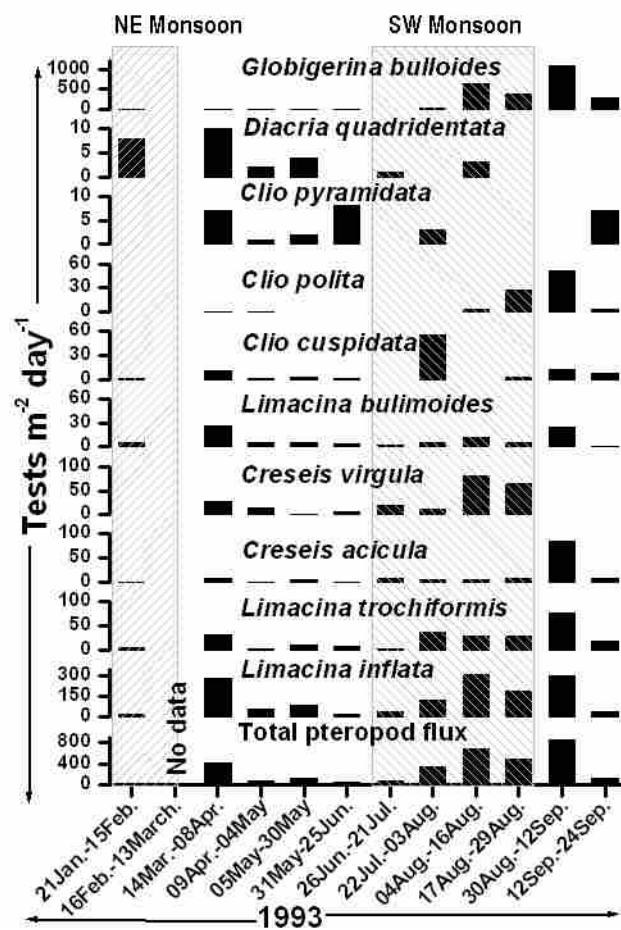


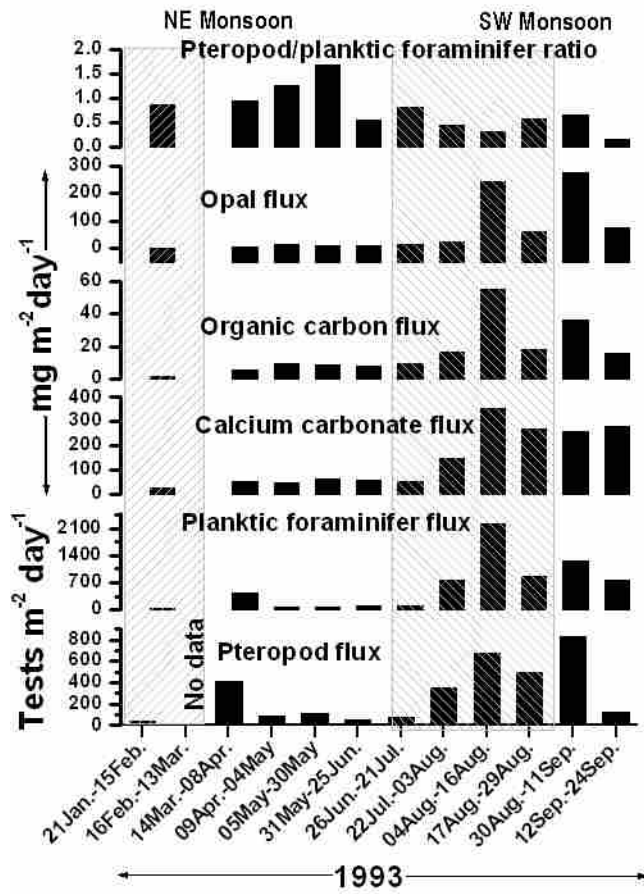
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