

Seasonal variability of the vertical fluxes of *Globigerina bulloides* (D'ORBIGNY) in the northern Indian Ocean

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With 8 tables and 4 text-figures

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Abstract

Settling particles intercepted using time-series sediment traps at seven locations in the northern Indian Ocean have been examined for the spatial and temporal variability in the distribution and fluxes of *Globigerina bulloides* (D'ORBIGNY). In general, *G. bulloides* exhibits a bimodal distribution pattern related to the summer and winter monsoons. Its fluxes increase from east to west in the Arabian Sea, and from north to south in the Bay of Bengal. They show a good correlation with sea surface temperature (SST) at three sites located in the central and southern Arabian Sea and in the southern Bay of Bengal. The observed relationship between SST and shell size is more complex with the length of cooling period rather than SST differences influencing the shell size.

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Zusammenfassung

Die räumliche und saisonale Variabilität der Verbreitung und der vertikalen Flußraten von *Globigerina bulloides* (d'ORBIGNY) wurden mit Hilfe von Sinkstoffproben aus kontinuierlichen Sedimentfallenexperimenten an sieben Stationen im nördlichen Indischen Ozean untersucht. Im allgemeinen zeigt *G. bulloides* bimodale Verbreitungsmuster, die mit dem Sommer- und Wintermonsoon zusammenhängen. Ihre Flußraten nehmen im Arabischen Meer vom Osten nach Westen und im Golf von Bengalen vom Norden nach Süden zu. Sie korrelieren mit der Oberflächentemperatur (SST) an den zentralen und südlichen Stationen im Arabischen Meer sowie im südlichen Golf von Bengalen. Die beobachtete Beziehung zwischen SST und Gehäusegröße ist komplexer. Die Gehäusegröße wird vielmehr von der Länge der Abkühlungsperiode beeinflußt als von den SST-Unterschieden.

1. Introduction

Globigerina bulloides, a sub-polar spinose planktonic foraminifer, dominates the sub-tropical and tropical assemblages in the Indian Ocean in response to characteristic summer monsoon upwelling. Abundance of *G. bulloides* is negatively correlated with SST and positively with nutrient contents (PRELL & CURRY, 1981; PRELL, 1984; CULLEN & PRELL, 1984; HUTSON & PRELL, 1980).

A number of proxy indicators have been employed to obtain information on upwelling-related paleoproductivity. One such proxy is the planktonic foraminifer species *Globigerina bulloides*. PRELL & CURRY (1981) have found an inverse relationship between sea surface temperature (SST) and relative abundances of *G. bulloides* in sediments from the Arabian Sea. PRELL & STREETER (1982) established a relationship between SST and *G. bulloides* as a paleo-monsoonal upwelling index. CLEMENS & PRELL (1990) correlated grain size distribution of the lithogenic fraction from a core in the Arabian Sea and showed close parallel relation with wind strength and *G. bulloides*.

Studies carried out by many others on planktonic foraminifera from the northern Indian Ocean have also demonstrated that the abundance of *G. bulloides* in the faunal assemblage is an indicator of upwelling (ZOBEL, 1971; BÉ & TOLDERLUND, 1971; BÉ & HUTSON, 1977). This inference was largely based on the study of fossil assemblages but also a few zooplankton samples. Recently, CURRY (1992) have also inferred upwelling based on abundance of *G. bulloides* flux in sediment traps from the Arabian Sea.

In order to understand the response of *G. bulloides* to seasonally changing hydrography in the northern Indian Ocean, we studied samples collected by time-series sediment traps. The samples were collected from seven locations covering the various oceanographic regimes in the northern Indian Ocean, such as the eutrophic regime in the western Arabian Sea, the oligotrophic regime in the southern Arabian Sea as well as the regions of very distinct salinity patterns from north to south in the Bay of Bengal.

2. Material and methods

The samples are from an ongoing experiment in the northern Indian Ocean which forms part of a collaborative programme between the National Institute of Oceanography (India) and the University of Hamburg (Germany) in marine geology and oceanography. Time-series sediment trap moorings were deployed at selected locations (Fig. 1, Tab. 1). For details see NAIR et al. (1989) and ITTEKOT et al. (1991). The details of sampling

schedules are shown in Tab. 2a-g. Methods of sampling and foraminiferal analyses are reported elsewhere (CURRY et al. 1992). Samples from the shallow traps are considered for the present investigations.

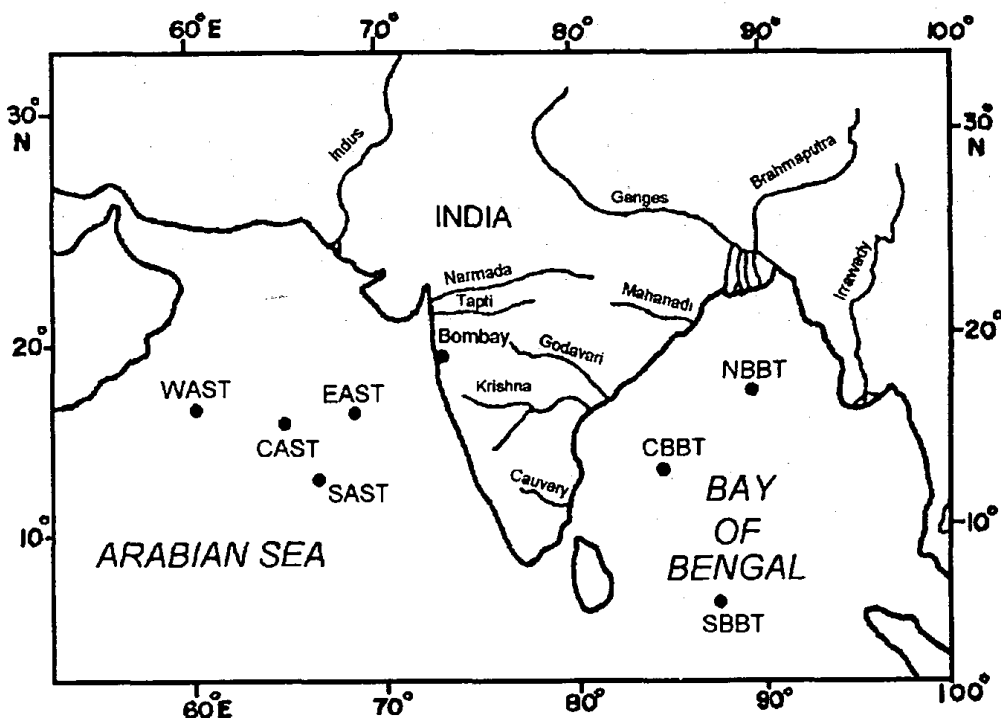


Fig. 1: Location of sediment trap moorings.

3. Results

The northern Indian Ocean, particularly the Arabian Sea, is an ideal area to study biological response to upwelling triggered by summer monsoon winds. Data sets from the western (WAST), central (CAST); eastern (EAST) and southern Arabian Sea (SAST) as well as from three trap locations in the Bay of Bengal [northern (NBBT), central (CBBT)

Area	Position	Water depth	Trap depth	Sampling interval	Duration
WAST	Lat 16 20	4016	1051	20.11.86-02.05.87	12.6
	Long 60 30			12.05.87-21.10.87	12.5
CAST	Lat 14 30	3920	0834	20.11.86-02.05.87	12.6
	Long 64 45			12.05.87-21.10.87	12.5
EAST	Lat 15 30	3776	1205	20.11.86-02.05.87	12.6
	Long 68 45			12.05.87-21.05.87	12.5
SAST	Lat 13 08	4075	1654	22.12.92-09.11.93	26(1-8)
	Long 67 07				09(9-13)
NBBT	Lat 17 27	2263	0968	02.11.88-19.10.89	26.0
	Long 89 36				
CBBT	Lat 13 09	3259	0955	02.11.88-19.10.89	26.0
	Long 84 21				
SBBT	Lat 04 06	4017	1036	05.02.92-15.12.92	26.0

Tab. 1: Sediment trap mooring locations, water depth (m), trap depth (m), sampling period, sampling interval (days).

and southern (SBBT)] have been used in the discussion (Fig. 1, Tab. 1). Also, the data reported by CURRY et al. (1992) for WAST, CAST and EAST and by GUPTHA et. al. (in press) for NBBT and CBBT have been included.

3.1. Arabian Sea

3.1.1 Western Arabian Sea (WAST)

The western Arabian Sea is characterised by eutrophic conditions due to intense upwelling caused by open ocean Ekman divergence (BAUER et al., 1991). The annual flux of *G. bulloides* ranging from 0-11417 shells $m^{-2} d^{-1}$, highest in the Arabian Sea, is largely confined to the 125-250 μm fraction followed by a few shells in the 250-500 μm fraction (CURRY et al., 1992). The total flux of this species displays a bimodal distribution pattern of which primary peak is invariably associated with the SW monsoon during July to early

Cup No.	Period from - to (d/m/y) - (d/m/y)	<i>Globigerina bulloides</i> size distribution (flux / m^2 /day)		
		>125 μm	>250 μm	>500 μm
<i>Western Arabian Sea (WAST)</i>				
1.	19.11.86-01.12.86	213	30	0
2.	02.12.86-14.12.86	203	0	0
3.	15.12.86-24.12.86	568	20	0
4.	24.12.86-08.01.87	132	20	0
5.	09.01.87-21.01.87	558	30	0
6.	22.01.87-02.02.87	629	80	0
7.	02.02.87-15.02.87	442	20	0
8.	16.02.87-27.02.87	30	10	0
9.	27.02.87-12.03.87	20	0	0
10.	13.03.87-25.03.87	0	0	0
11.	26.03.87-06.04.87	0	0	0
12.	07.04.87-19.04.87	0	0	0
13.	20.04.87-01.05.87	0	0	0
1.	12.05.87-24.05.87	50	0	0
2.	24.05.87-06.06.87	30	0	0
3.	07.05.87-18.05.87	0	0	0
4.	19.05.87-01.07.87	181	0	0
5.	02.07.87-13.07.87	624	0	0
6.	14.07.87-26.07.87	1297	231	0
7.	27.07.87-07.08.87	2706	1157	10
8.	08.08.87-20.08.87	3963	614	0
9.	21.08.87-01.09.87	5824	141	0
10.	02.09.87-14.09.87	10663	1157	0
11.	15.09.87-26.09.87	10200	1217	0
12.	27.09.87-09.10.87	1891	91	0
13.	10.10.87-21.10.87	0	0	0

Tab. 2a: Details of sampling schedules along with *G. bulloides* data (flux/ m^2 /day) in different size fractions.

October. Highest number of shells were observed at the end of this season in September. The secondary peak is associated with the NE monsoon period during November - February. On the other hand, the foraminiferal assemblage during most of the intermonsoon period of March and April is virtually devoid of *G. bulloides* (Fig. 2a). CURRY et al. (1992) reported from the western Arabian Sea a ten fold increase between WAST and rest of the Arabian Sea in the production of total planktonic foraminifers of which almost half was comprised of *G. bulloides*. Furthermore, all foraminiferal species in these sediment traps significantly increase in production during the monsoons, while during intermonsoon intervals the production is very low. The foraminiferal assemblage is reported to be dominated by *G. bulloides* and *G. glutinata* during the southwest monsoon.

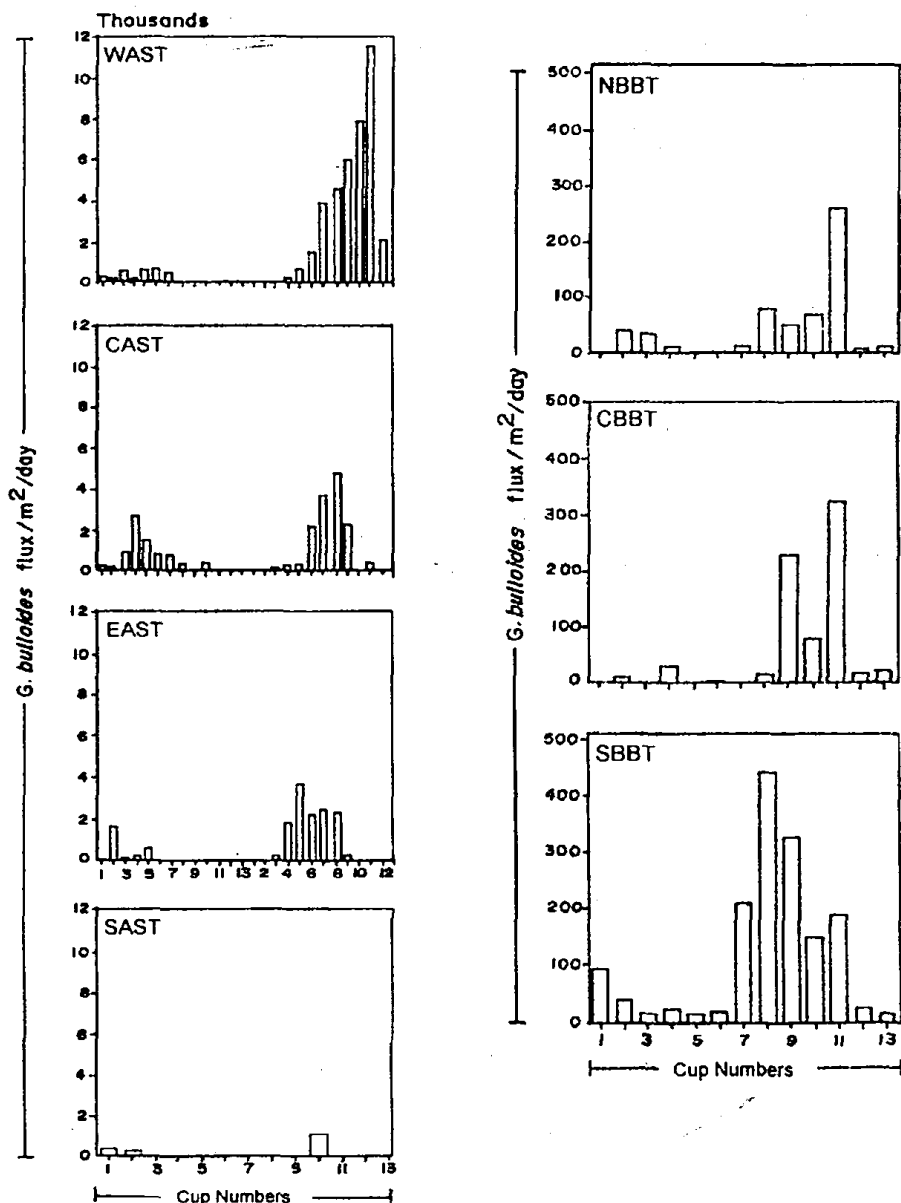


Fig.2: Distribution pattern of *G. bulloides* both in the Arabian Sea (a) and Bay of Bengal (b).

3.1.2 Central Arabian Sea (CAST)

Despite the fact that the central Arabian Sea is far from the region of WAST, it is considered to be under the influence of mid ocean upwelling regions off the Arabian coast (BAUER et. al, 1991). Besides, depending on the intensity of winds a deepening of the mixed layer from 30-40 m during the intermonsoon to about 100 m during the SW monsoon period is found to occur (HASTENRATH & LAMB, 1979; BAUER et al. 1991). *Globigerina bulloides* is one of the most abundant species also at this trap location and range from 0 to 4657 shells $m^{-2} d^{-1}$ (Fig. 2a). As in WAST, this species largely falls in the 125-250 μm size fraction, with lesser numbers in the 250-500 μm fraction.

The flux of *G. bulloides* continues to display bi-modal distribution pattern associated with the southwest and northeast monsoons. As seen in WAST, the highest abundance peak is associated with the SW monsoon. Contrary to WAST and EAST, the flux of this species tends to increase substantially during the winter monsoon, in the month of February. *G. bulloides* is however absent during the intermonsoon months of March and April. CURRY et al. (1992) reported that the foraminiferal flux in the central Arabian Sea exhibits somewhat the same seasonal pattern as the in the western Arabian Sea, but overall, the rate of production reduced to about one half as large.

Cup No.	Period from - to (d/m/y) - (d/m/y)	<i>Globigerina bulloides</i> size distribution (flux / m^2 /day)		
		>125 μm	>250 μm	>500 μm
<i>Central Arabian Sea (CAST)</i>				
1.	19.11.86-01.12.86	304	10	10
2.	02.12.86-14.12.86	142	0	0
3.	15.12.86-24.12.86	841	100	0
4.	24.12.86-08.01.87	2533	190	0
5.	09.01.87-21.01.87	1288	170	0
6.	22.01.87-02.02.87	776	40	0
7.	02.02.87-15.02.87	750	10	0
8.	16.02.87-27.02.87	253	40	0
9.	27.02.87-12.03.87	0	0	0
10.	13.03.87-25.03.87	354	40	0
11.	26.03.87-06.04.87	0	0	0
12.	07.04.87-19.04.87	0	0	0
13.	20.04.87-01.05.87	0	0	0
1.	12.05.87-24.05.87	50	10	0
2.	24.05.87-06.06.87	60	0	0
3.	07.05.87-18.05.87	60	20	0
4.	19.05.87-01.07.87	231	0	0
5.	02.07.87-13.07.87	300	20	0
6.	14.07.87-26.07.87	1690	382	0
7.	27.07.87-07.08.87	3118	513	0
8.	08.08.87-20.08.87	4556	101	0
9.	21.08.87-01.09.87	2133	40	0
10.	02.09.87-14.09.87	0	0	0
11.	15.09.87-26.09.87	302	0	0
12.	27.09.87-09.10.87			
13.	10.10.87-21.10.87			

Tab. 2b: Details of sampling schedules along with *G. bulloides* data (flux/ m^2 /day) in different size fractions.

3.1.3 Eastern Arabian Sea (EAST)

The eastern Arabian Sea is characterised by a weak or lack of upwelling and primary productivity during both NE and SW monsoon periods. The flux of *G. bulloides* at this location ranges from 0-3651 shells $m^{-2} d^{-1}$ (Fig. 2a). This species falls in the 125-250 μm size class with a few shells encountered in the 250-500 μm size fraction during SW monsoon (mid July). The peak abundance during August-September is largely confined to 125-250 μm size fraction, whereas increase in shell size to 250-500 μm was observed during mid July. *Globigerina bulloides* is absent during February-April (Fig. 2a). Curry et al. (1992) observed the lowest foraminiferal production in this trap, which is about one third of the total flux of those at WAST. Further, as at CAST, *G. bulloides* and *G. ruber* dominate the planktonic foraminiferal assemblage at EAST (CURRY et al. 1992).

Cup No.	Period from - to (d/m/y) - (d/m/y)	<i>Globigerina bulloides</i> size distribution (flux / m^2 /day)		
		>125 μm	>250 μm	>500 μm
<i>Eastern Arabian Sea (EAST)</i>				
1.	19.11.86-01.12.86	0	0	0
2.	02.12.86-14.12.86	1287	369	0
3.	15.12.86-24.12.86	152	10	0
4.	24.12.86-08.01.87	233	0	0
5.	09.01.87-21.01.87	557	80	0
6.	22.01.87-02.02.87	0	0	0
7.	02.02.87-15.02.87	0	0	0
8.	16.02.87-27.02.87	0	0	0
9.	27.02.87-12.03.87	0	0	0
10.	13.03.87-25.03.87	0	0	0
11.	26.03.87-06.04.87	0	0	0
12.	07.04.87-19.04.87	40	0	0
13.	20.04.87-01.05.87	50	0	0
1.	12.05.87-24.05.87	20	0	0
2.	24.05.87-06.06.87	60	0	0
3.	07.05.87-18.05.87	161	0	0
4.	19.05.87-01.07.87	785	1086	0
5.	02.07.87-13.07.87	3078	573	0
6.	14.07.87-26.07.87	2183	60	0
7.	27.07.87-07.08.87	1992	453	0
8.	08.08.87-20.08.87	1911	352	0
9.	21.08.87-01.09.87	262	0	0
10.	02.09.87-14.09.87	0	0	0
11.	15.09.87-26.09.87			
12.	27.09.87-09.10.87			
13.	10.10.87-21.10.87			

Tab. 2c: Details of sampling schedules along with *G. bulloides* data (flux/ m^2 /day) in different size fractions.

Cup No.	Period from - to (d/m/y) - (d/m/y)	<i>Globigerina bulloides</i> size distribution (flux /m ² /day)		
		>125 µm	>250 µm	>500 µm
<i>Southern Arabian Sea (SAST)</i>				
1.	25.12.92-19.01.93	412	11	1
2.	20.01.93-14.02.93	336	15	0
3.	15.02.93-12.03.93	62	2	0
4.	13.03.93-07.04.93	11	0	1
5.	08.04.93-03.05.93	4	0	0
6.	04.05.93-29.05.93	3	0	0
7.	30.05.93-24.06.93	0	0	0
8.	25.06.93-20.07.93	0	6	1
9.	21.07.93-02.08.93	46	3	0
10.	03.08.93-15.08.93	1196	150	1
11.	16.08.93-28.08.93			
12.	29.08.93-10.09.93			
13.	11.09.93-23.09.93			

Tab. 2d: Details of sampling schedules along with *G. bulloides* data (flux/m²/day) in different size fractions.

3.1.4 Southern Arabian Sea (SAST)

This trap is situated in the south eastern Arabian Sea, characterised by oligotrophic conditions. At this location, the flux of *G. bulloides* ranges from 3-1347 shells m⁻² d⁻¹ (Fig. 2a) displaying a bi-modal distribution pattern, in which the primary and secondary peaks are generally associated with the SW and NE monsoon, respectively. This species is largely confined to the 125-250 µm size fraction. This data set was collected during 1992-93, six years after the previously treated Arabian Sea data (Tab. 2d). The highest number of shells m⁻² d⁻¹ is associated with the early days of August (Fig. 2a).

3.2 Bay of Bengal

Like the Arabian Sea *G. bulloides* is the species observed in the greatest abundance in the Bay of Bengal (GUPTHA et al., in press). Its flux is also seasonally biased towards

Cup No.	Period from - to (d/m/y) - (d/m/y)	<i>Globigerina bulloides</i> size distribution (flux /m ² /day)		
		>125 µm	>250 µm	>500 µm
<i>Northern Bay of Bengal (NBBT)</i>				
1.	02.11.88-29.11.88	0	0	0
2.	29.11.88-26.12.88	33	8	0
3.	26.12.88-22.01.89	32	4	0
4.	22.01.89-18.02.89	9	4	0
5.	18.02.89-17.03.89	1	1	0
6.	17.03.89-13.04.89	4	1	0
7.	03.04.89-10.05.89	11	5	0
8.	10.05.89-06.06.89	17	64	0
9.	06.06.89-03.07.89	41	13	1
10.	03.07.89-30.07.89	63	9	0
11.	30.07.89-26.08.89	149	113	0
12.	26.07.89-22.09.89	9	2	0
13.	22.09.89-19.10.89	8	8	8

Tab. 2e: Details of sampling schedules along with *G. bulloides* data (flux/m²/day) in different size fractions.

maximum fluxes during the SW monsoon and it also shows marginal increase associated with the NE monsoon.

3.2.1 Northern Bay of Bengal (NBBT)

The northern most trap (NBBT) is situated in the vicinity of the fresh water influence of Ganges and Brahmaputra Rivers. The flux of *G. bulloides* ranges from 2-262 shells $m^{-2} d^{-1}$ and like in the Arabian Sea largely confined to the 125-250 μm size class. The flux does not display a distinct bimodal distribution. However, abundance peak is observed during the SW monsoon, while it is lower during the NE monsoon period of December - February (Fig. 2b).

Cup No.	Period from - to (d/m/y) - (d/m/y)	<i>Globigerina bulloides</i> size distribution (flux / m^2 /day)		
		>125 μm	>250 μm	>500 μm
<i>Central Bay of Bengal (CBBT)</i>				
1.	02.11.88-29.11.88	0	0	0
2.	29.11.88-26.12.88	8	1	0
3.	26.12.88-22.01.89	0	0	0
4.	22.01.89-18.02.89	24	6	0
5.	18.02.89-17.03.89	0	0	0
6.	17.03.89-13.04.89	2	2	0
7.	03.04.89-10.05.89	0	0	0
8.	10.05.89-06.06.89	11	5	0
9.	06.06.89-03.07.89	69	162	0
10.	03.07.89-30.07.89	20	60	0
11.	30.07.89-26.08.89	190	136	0
12.	26.07.89-22.09.89	15	4	0
13.	22.09.89-19.10.89	20	5	0

Tab. 2f: Details of sampling schedules along with *G. bulloides* data (flux/ m^2 /day) in different size fractions.

Cup No.	Period from - to (d/m/y) - (d/m/y)	<i>Globigerina bulloides</i> size distribution (flux / m^2 /day)		
		>125 μm	>250 μm	>500 μm
<i>Southern Bay of Bengal (SBBT)</i>				
1.	05.02.92-07.02.92	96	0	0
2.	08.02.92-04.03.92	35	4	0
3.	05.03.92-30.03.92	15	0	0
4.	31.03.92-25.04.92	21	3	0
5.	26.04.92-21.05.92	15	0	0
6.	22.05.92-16.06.92	16	2	0
7.	17.06.92-12.07.92	153	55	1
8.	13.07.92-07.08.92	357	94	0
9.	08.08.92-02.09.92	255	74	0
10.	03.09.92-28.09.92	136	15	1
11.	29.09.92-24.10.92	163	27	0
12.	25.10.92-19.11.92	26	3	0
13.	20.11.92-15.12.92	16	2	0

Tab. 2g: Details of sampling schedules along with *G. bulloides* data (flux/ m^2 /day) in different size fractions.

3.2.2 Central Bay of Bengal (CBBT)

In the Central Bay of Bengal the *G. bulloides* flux varies from 4-326 shells $m^{-2} d^{-1}$. Although there is some variation in size, it is largely represented by 125-250 μm size class, except for cups 9-11 during July - August where > 70% are in the size range of 250-500 μm . Highest abundance of *G. bulloides* are found to occur during the SW monsoon. During September its flux declines to about 40% of total foraminiferal flux, while its production during the NE monsoon period is very insignificant (Fig. 2b).

3.2.3 Southern Bay of Bengal (SBBT)

This trap is situated further down southeast of CBBT in the equatorial region. The flux of *G. bulloides* ranges from 0-460 shells $m^{-2} d^{-1}$. *G. bulloides* at this trap location also displays distinct seasonality to both SW and NE monsoons and it is absent during the intermonsoon months of March-April (Fig. 2b).

4. Discussion

Based on the available data base including that of CURRY et al. (1992) and GUPTHA et al. (in press), on *G. bulloides* from seven sediment trap locations in the northern Indian Ocean (Arabian Sea and Bay of Bengal), it is evident that the annual average flux of *G. bulloides* tends to decrease significantly across the Arabian Sea from 11417 shells $m^{-2} d^{-1}$ at WAST to 1346 shells $m^{-2} d^{-1}$ at SAST (Fig. 2a). Similarly, in the Bay of Bengal the seasonal variation is very distinct from north to south. The *G. bulloides* annual flux progressively increases from 262 shells $m^{-2} d^{-1}$ at NBBT to 451 shells $m^{-2} d^{-1}$ at SBBT (Fig. 2b). CURRY et al. (1992) observed that in general the foraminiferal production is higher in the western Arabian Sea trap than in the central and eastern Arabian Sea traps. They also report that the variation in abundance of *G. bulloides* across the Arabian Sea during the periods of intense upwelling increased by a factor of three between WAST and EAST. Similarly, GUPTHA et al. (in press) observed the variation in the flux of *G. bulloides* from north to south in the Bay of Bengal.

The increase in flux of *G. bulloides* at WAST may be explained by the fact that the summer monsoon winds over the western Arabian Sea result in the upwelling of cold nutrient-rich waters accompanied by high productivity along the coast as well as in the open sea (CURRIE et al., 1973; SMITH & BOTTERO, 1977; PRELL & CURRY, 1981; PRELL et al., 1990; BANSE & ENGLISH, 1993). For the summer monsoon of 1986, NAIR et al. (1989) reported that the waters from Somali-Arabian upwelling centres were advected up to 60°E, i.e., as far as WAST trap location.

The increase in this region of the upwelling indicator species *G. bulloides* supports the occurrence of open-ocean upwelling in the western Arabian Sea or advection of cool nutrient-rich water from the coast (LUTHER et al., 1990). Because open ocean upwelling seems to occur in the central Arabian Sea (CAST) due to the influence of Ekman type of divergence in the western Arabian Sea, and/or deepening of the mixed layer caused by intense low level strong winds during the SW monsoon, this trap site also witnesses considerable biological productivity. However, in comparison to WAST, its intensity is less; hence *G. bulloides* decreased to 0-4657 shells at CAST. Further east and southeastwards (EAST and SAST), the production of *G. bulloides* declines further which

may be due to low and/or no productivity (oligotrophic conditions) (SASTRY & RAMESH BABU, 1985). Based on vertical hauls, GUPTHA et al. (1994), have also reported significantly low frequency of *G. bulloides* during the late summer monsoon period in the central part of eastern Arabian Sea and attributed this to warming of the surface water in combination with the deepening of the mixed layer. According to WYRTKI (1971), the southern Arabian Sea always experiences lower nutrient concentrations at all depths in contrast to the corresponding depths in the northern Arabian Sea.

Nutrient inputs from rivers as also from entrainment of subhalocline layers in the Bay of Bengal would enhance nutrient enrichment during the SW monsoon particularly in river plumes (ITTEKKOT et al., 1991). Although there is fertility caused by river plumes at NBBT, unlike true oceanic upwelling, the river influence is well represented by a low salinity indicator species *Neogloboquadrina dutertrei*, in association with *G. bulloides* as a secondary species. On the other hand, at CBBT, the region might be influenced by both river plumes and by oceanic upwelling resulting in foraminiferal productivity predominantly represented by *G. bulloides* followed by *N. dutertrei*. Further south, at SBBT, the equatorial waters might be influenced by weak/and or no upwelling which, however, is not comparable in its strength to the upwelling in the Arabian Sea during the south west monsoon resulting in relatively higher productivity (VINOGRADOV, 1981).

It appears that the salinity factor is mainly responsible for decreasing abundance of *G. bulloides* in the Bay of Bengal as compared to the Arabian Sea, where in general coastal Ekman type as well as open-ocean type of upwelling prevails. ORTIZ & MIX (1992) reported

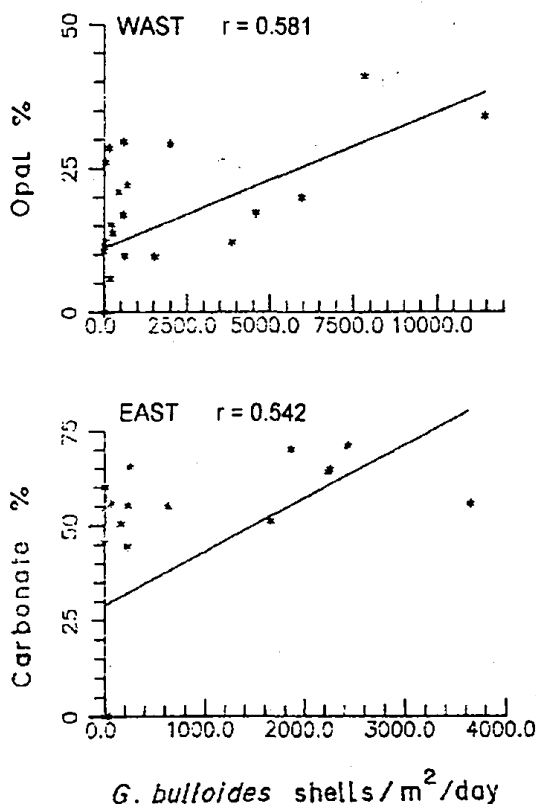


Fig. 3: Correlation of *G. bulloides* flux with opal (%) ($r=0.581$, $n=26$) and calcium carbonate (%) ($r=0.524$, $n=26$).

a bimodal distribution pattern of *G. bulloides* in the California Current over the year, attributing the peaks to be associated with summer and winter seasons. Further, they also attributed the summer peak to upwelling and the winter peak to immigration of subarctic population. In the present study, the secondary peak of *G. bulloides* associated with the winter period at CAST in the Arabian Sea may be attributed to winter fertilisation. Supporting this view, BANSE & ENGLISH (1993) reported high phytoplankton values during the winter period from satellite-based phytoplankton pigment data from the Arabian Sea.

In order to determine the relationship between the geochemical variables (organic carbon, opal and calcium carbonate) and the abundance of *G. bulloides* flux to understand the upwelling phenomenon, we compared them from three locations in the Arabian Sea (WAST, CAST and EAST) and two stations in the Bay of Bengal (NBBT and CBBT) from where such data were available. Except for opal at WAST and CaCO_3 at EAST, which display good correlation (Fig. 3), no other geochemical parameters showed any sort of relation with *G. bulloides*. The reason why opal shows positive correlation with *G. bulloides* may be due to supply of high flux of opal. HAAKE et al. (1993) reported that the biogenic opal reaches values as high as 50% of total flux at WAST during the SW monsoon, which is almost entirely comprised of a diatom, *Rhizosolenia* sp., characteristic of upwelling. Similarly, the positive correlation between *G. bulloides* and CaCO_3 at EAST in the eastern Arabian Sea during the summer monsoon may be attributed to less productivity and less organic carbon production, which otherwise would have affected CaCO_3 dissolution with formation of a very weak carbonic acid. However, SHIMMIELD et al. (1990) concluded that both calcium carbonate and silica are apparently unreliable indicators of paleoproductivity in the NW Arabian Sea due to lithogenic dilution and/or dissolution.

The present study also does not show any correlation between organic carbon and upwelling or productivity as it was also the case in Arabian Sea (PRELL, 1984; CLEMENS & PRELL, 1990). EMEIS et al. (1995) have also confirmed that in the Arabian Sea, the organic carbon accumulation rates are misleading as productivity indicators as the high variability of sediment such as eolian input is introduced. PAROPKARI et al. (1991) critically examined the productivity of organic enrichment along the western Indian margin and concluded that there is no correspondence between productivity and organic enrichment. But, DIVAKAR NAIDU et al. (1992) reported 30-40% *G. bulloides* from the sediment of the south western continental margin of India showing good positive correlation between organic carbon and *G. bulloides*. They also found that the intensity of upwelling could be delineated based on the abundance of *G. bulloides*. RAO et al. (1993) reported *G. bulloides* in very small quantities from the sediment of the SW Arabian Sea only. The reason for this discrepancy between DIVAKAR NAIDU et al. (1992) and RAO et al. (1993) is unclear. Furthermore, BURCKLE (1989) reported diatom-barren zones along the west and east coast of India reflecting the productivity. Previously, a strong correlation between diatom productivity and nutrients in surface waters and diatom accumulation on the seafloor has been noted by SCHRADER (1970), BERGER (1976) and LEINEN et al. (1986).

Since *G. bulloides* displays negative correlation with sea surface temperature (PRELL & CURRY, 1981; PRELL & STREETER, 1982), the flux of *G. bulloides* in the present study from the northern Indian Ocean has been correlated with the monthly mean temperatures (SST) obtained from the Climate Atlas of HASTENRATH & LAMB (1979). Except for CAST ($r = -0.346$, $n=26$), SAST ($r = -0.537$, $n=10$) and SBBT ($r = -0.412$, $n=13$), none of the three other trap locations in the Arabian Sea and Bay of Bengal displayed any correlation. The correlation coefficient is significant at 90.0% confidence level for samples at CAST,

SAST and SBBT (Fig. 4). The correlation coefficient ($r=0.581$, $n=26$) between *G. bulloides* flux and opal at WAST is significant at 99.9% confidence level. Similarly, when carbonate was correlated with *G. bulloides* flux at EAST the correlation coefficient ($r= 0.524$, $n=26$) is also significant at 99.9% confidence level.

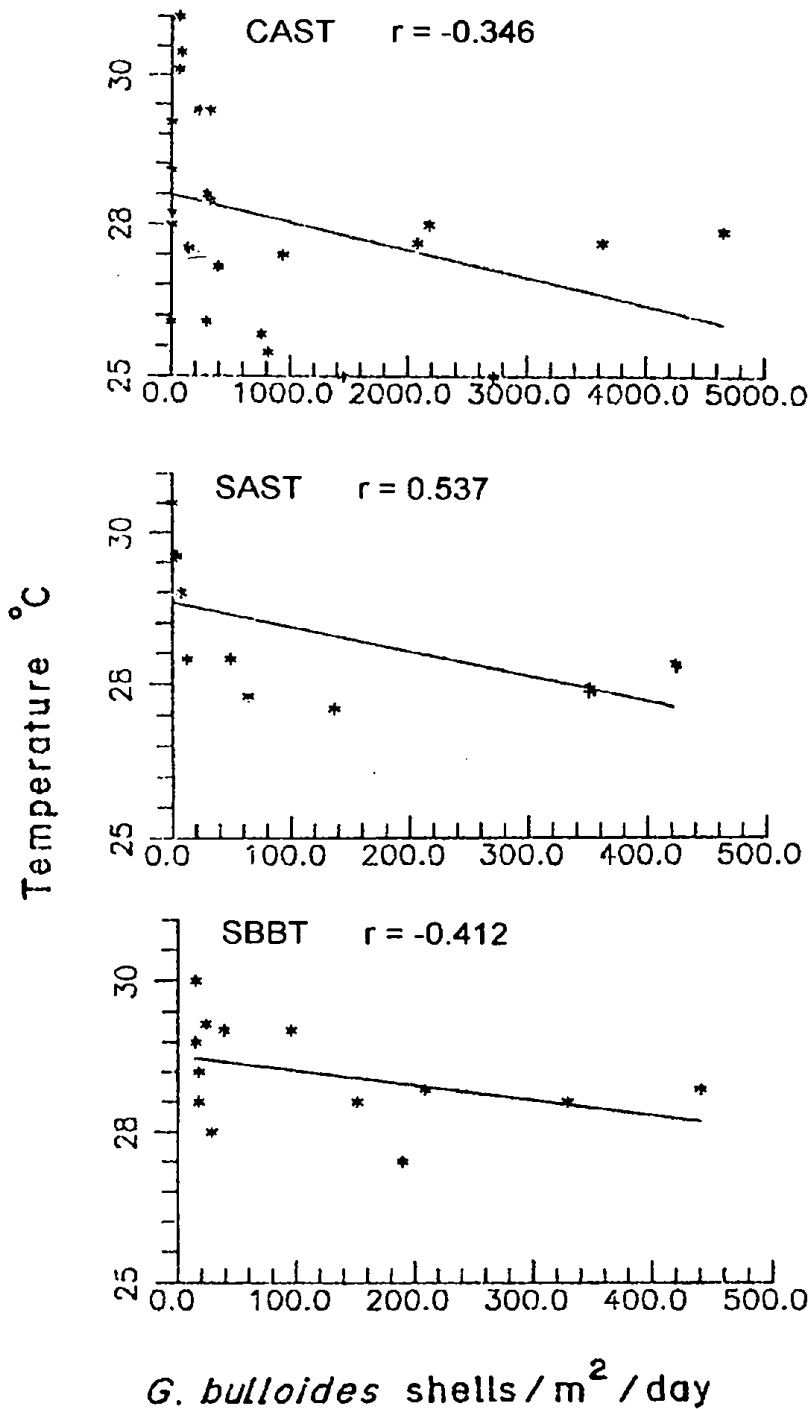


Fig. 4: Correlation between *G. bulloides* flux and SST at CAST ($r= -0.346$, $n=26$), SAST ($r= -0.537$, $n=10$) and SBBT ($r= -0.412$, $n=13$).

Although the abundance of *G. bulloides* has been extensively used as a proxy indicator (PRELL & CURRY 1981; PRELL, 1984, HUTSON & PRELL, 1980; CULLEN & PRELL, 1984), our studies suggest that *G. bulloides* is not necessarily the only species which can be used as an indicator of upwelling or nutrient enrichment in the northern Indian Ocean. For example, in NBBT, *Neogloboquadrina dutertrei*, a low salinity indicator species outnumbers *G. bulloides* (GUPTHA et al., in press). Although *G. bulloides* shows increased abundance during the upwelling period, it is evident from sediment traps from the San Pedro Basin and other regions of the Pacific that this species thrives in a wide range of thermal environments and not limited to upwelling habitat alone (SAUTTER & THUNELL, 1991). Although, *G. bulloides* at EAST, SAST and SBBT trap locations do show relative peak abundances during the SW monsoon, it may not be necessary to suggest upwelling as these regions are characterised by weak upwelling and low productivity. Besides, it has been observed that *G. bulloides* invariably displays a bimodal pattern wherein the primary abundance peaks are generally associated with the SW monsoon period, while the secondary peaks to NE monsoon. Furthermore, it is noticed that the winter peak abundance in the central Arabian Sea trap exhibits comparatively a higher flux of *G. bulloides*, in contrast to other trap locations (WAST, EAST and SAST) in the Arabian Sea. This may be attributed to the fact that the winter bloom of phytoplankton production occurring in the northern and central parts of the Arabian Sea (BANSE & ENGLISH, 1993), might have facilitated higher production of *G. bulloides*. In contrast, in the Bay of Bengal, the scenario is somewhat different, where, winter peak abundances are very insignificant. Similarly, ITTEKKOT et al. (1991) have also reported uniformly low particle fluxes during NE monsoon and intermonsoon periods for the Bay of Bengal.

Our studies have revealed that the shells of *G. bulloides* fall largely into 125-250 μm size range. However, at EAST and CBBT, the size of this species tends to vary significantly, exhibiting an increase in size to 250-500 μm during the summer monsoon months. MALMGREN & KENNETT (1976) have shown a general increase in average size of *G. bulloides* with decreasing water temperature. Besides, they also stated that there is a positive correlation between general size and the frequency of *G. bulloides* suggesting optimum growth, resulting greater size. MALMGREN & KENNETT (1978) reported from the sediments of Southern Indian Ocean that the mean sizes are larger during cool episodes and smaller during warmer periods. Recently DIVAKAR NAIDU & MALMGREN (1995) reported from an ODP Hole 723 A from the Oman margin that the test size increases in nutrient rich upwelled waters. THUNELL & REYNOLD (1984) also reported increase in shell size from Panama Basin during June-July when fluxes are high suggesting the occurrence of maximum test size when the conditions are optimal for production.

However, despite the fact that the decrease of SST is found to be as high as 10°C off the Arabian coast during May - July (SASTRY & RAMESH BABU, 1985), the shell size remains < 250 μm at WAST. In contrast, the shell size tends to grow considerably > 250 μm at EAST, where the SST drop is just 2-3°C. This may be explained by the high rate of phytoplankton production during upwelling which diminishes the rate of cooling and enhances heating (SATYENDRANATH et al., 1991). Such an interruption in cooling must have resulted in very insignificant growth rates. Although, the rate of cooling during May - July is about 2-3°C at EAST, the period of cooling might have continued over a longer duration, since there is no phytoplankton production comparable to that at WAST which would otherwise have enhanced the heating of surface layers. Such an extended cooling might have created optimum conditions for shell growth.

In the Bay of Bengal, the extended cooling of surface waters might have been accomplished by a combination of factors, such as coastal upwelling as also the fresh water influx during summer monsoon resulting in extended optimum cool water conditions with which slow and steady shell growth must have been accomplished. This could explain the occurrence of shells >250 µm at CBBT.

5. Conclusions

The fluxes of *G. bulloides* exhibit seasonality in pulse with the southwest and northeast monsoons. They progressively increase from the eastern to the western Arabian Sea, and also from the northern to the southern Bay of Bengal. The fluxes display negative correlation with SST only at CAST, SAST and SBBT. The shell size largely falls into the 125-250 µm fraction. Increasing shell size noticed during the early SW monsoon (June) in the Arabian Sea (EAST) and central Bay of Bengal (CBBT) may be attributed to prolonged periods of surface water cooling which facilitates slow and steady growth.

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