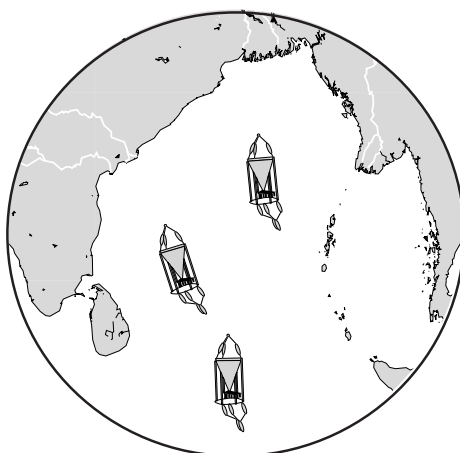
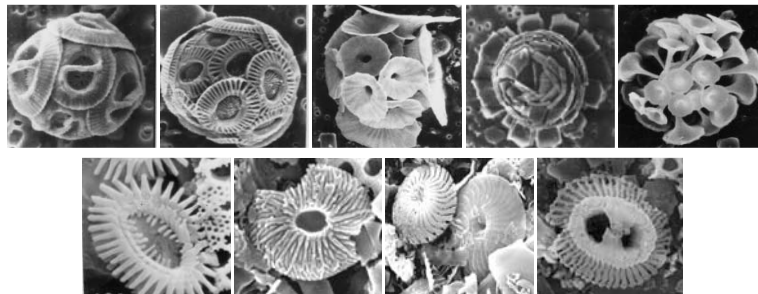


Seasonal variation of the flux of living coccolithophore communities in the Bay of Bengal and their implication on hydrography



THESIS SUBMITTED TO
THE DEPARTMENT OF MARINE SCIENCES
GOA UNIVERSITY TALEIGAO PLATEAU, GOA



FOR THE DEGREE OF
DOCTOR OF PHILOSOPHY

IN
MARINE SCIENCES

BY
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SEPTEMBER 2006

CERTIFICATE

*This is to certify that the thesis entitled “**Seasonal variation of the flux of living coccolithophore communities in the Bay of Bengal and their implication on hydrography**” submitted by **Ms. Lina P. Mergulhao** for the award of the degree of **Doctor of Philosophy in Marine Sciences** is based on her original studies carried out by her under my supervision. The thesis or any part thereof has not been previously submitted for any other degree or diploma in any university or institution.*

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STATEMENT

As required under the University ordinance 0.19.8 (VI), I state that the present thesis entitled **“Seasonal variation of the flux of living coccolithophore communities in the Bay of Bengal and their implication on hydrography”** is my original contribution and the same has not been submitted on any previous occasion. To the best of my knowledge the present study is the first comprehensive work of its kind from the area mentioned.

The literature related to the problem investigated has been cited. Due acknowledgements have been made wherever facilities and suggestions have been availed of.

(Lina P. Mergulhao)

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Acknowledgements

It is my privilege and honor to express my deep sense of gratitude to my guide Dr. M. V. S. Gupta, (Retired Scientist), National Institute of Oceanography, Goa for his guidance and help in the execution of this work. It is his sustained encouragement throughout even after his retirement that helped me to complete this work, without which it would not have been possible for me to complete it successfully.

I am also greatly indebted to Dr. V. S. N. Murty, Scientist, Physical Oceanography Division of the National Institute of Oceanography, Goa for his valued discussions, suggestions and keen interest in my research work. He was also very kind in providing relevant data on hydrography.

I thank Dr. S. R. Shetye, Director, National Institute of Oceanography, Goa, for his kind support, encouragement and providing facilities required for this work. Thanks are also due to Prof. V. Ittekkot one of the co-ordinators of the Indo-German bilateral Program for his continued support and encouragement in this work. Drs. Daniela Unger and Tim Rixen of the Center for Tropical Marine Ecology, Bremen, Germany are also thanked for providing necessary data.

I also thank Prof. G. N. Nayak (Head) and Dr. V. M. Matta (Co-guide) Department of Marine Sciences, Goa University for their encouragement and support throughout my work. My sincere thanks to Dr. R. Nigam, Dr. V. K. Banakar, Dr. P. C. Rao and Dr. D.V. Borole for their help and interest in this study.

Thanks are also due to Mr. A. Sardar and Mr. V. Khedekar for their assistance in the SEM analysis, Mr. Umesh Shirsat, Mr. Uchil and Mr. Mahale for their help in preparing photographs and figures and Mr. A.S. Muralinath for his assistance in the laboratory work.

I am very grateful to the Department of Ocean Development, captain and crew of ORV Sagar Kanya for their help and co-operation in collecting samples. I wish to express my thanks to the Council of Scientific and Industrial Research (CSIR), New Delhi, for the award of Senior Research Fellowship.

My friends Ms. Leena, Ms Kavita, Ms. Joereen, Dr. Hema, Ms. Valintina and Mr. Ramchandra were of great help in preparation of my thesis.

Last but not least, it is my sincere duty to thank my family for their perseverance, support, patience and encouragement throughout my work.

Finally, I am grateful to all those who have been helping me directly or indirectly in my endeavor.

Lina P. Mergulhao

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*Dedicated
to my beloved parents*

CHAPTER 1

Introduction

Chapter 1

INTRODUCTION

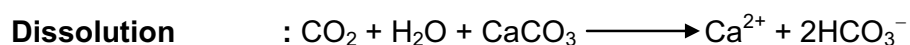
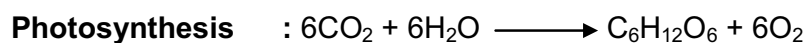
1.1 Introduction

The Bay of Bengal in the northeastern Indian Ocean is a semi enclosed basin covering an area of 2.2×10^6 km² which is about 0.6% of the world oceans (La Fond, 1966). This falls under the influence of the seasonally changing monsoon gyre of the Asian monsoon system (Wyrki, 1973). Unlike the Arabian Sea, the Bay of Bengal receives enormous quantity of fluvial inputs through the largest rivers in this region such as the Ganges and the Brahmaputra resulting in the formation of the world's largest deep sea fan. The majority of its annual average of 1.1×10^9 tons sediment is largely supplied between June-September periods only (Milliman and Meade, 1983). The other major contributors of terrigenous material to the Bay are the peninsular Indian rivers such as the Mahanadi, the Godavari, the Krishna and Cauvery which have their peak discharge during the later phase of SW (southwest) monsoon. Besides, enormous fresh water and suspended sediment discharge largely takes place during the SW monsoon period (Rao, 1979; Ittekkot et al., 1985, Ittekkot and Arain, 1986). Furthermore, this results in great changes in the surface salinity over the entire Bay of Bengal (Wyrki, 1973; Murty et al., 1990). Although this kind of oceanographic setting inhibits, does not prevent upwelling along the western part of the Bay (Rao, 1977; Shetye et al., 1991). Owing to its unique and diverse oceanographic conditions, it would be interesting to examine the effect of seasonally changing and interacting continental and oceanographic processes on marine biological processes and in particular on coccolithophores.

Coccolithophores are one of the most important primary producers living in the ocean representing a major group of autotrophic marine phytoplankton. These are unicellular phytoplankton with spherical or oval shapes of $< 20 \mu\text{m}$ in diameter comprising of two golden-brown pigment spots, a prominent nucleus, two flagella of equal length and a whip like *haptonema*. They are the members of the algal class *Prymnesiophyceae*

which are covered by tiny calcareous scales or plates called *coccoliths*, with a range in diameter from 3-15 μm . They live in the photic zone (0-200 m) and are very sensitive to any change in hydrographic conditions such as temperature, salinity, nutrients, sunlight etc. It has been reported that there are about 200 species of extant coccolithophores which occur worldwide with their highest diversity largely restricted to the temperate and subtropical regions (Okada and McIntyre, 1977). The coccoliths were first reported while examining chalk from the island of Rugen in the Baltic Sea by Ehrenberg (1836), while Wallich (1877) was first to describe the living coccolithophores. Geological records show that these coccolithophore fossils are as old as approximately 230 Ma found in Carnian Stage (earliest Late Triassic), although till recently it was believed to be of Jurassic in age.

In the recent years, coccolithophores have immensely gained attention of scientists world over as they make an important contributions to the oceanic primary production and also of their optical (albedo: masses of detached coccoliths substantially reflect incoming light) and biochemical (Dimethylsulphide-which acts as a source molecule of cloud nucleation) properties, which add additional feed back to the climate change (Westbroek et al., 1993). Besides, they also play a prominent role in the global carbon cycle, not merely as biological pump but also as an inorganic pump (Fig. 1.1). Understanding the role of phytoplankton in sequestering CO_2 is an important component of global climate change research in the recent years. Coccolithophores and diatoms are the two most important groups of phytoplankton, which are extensively studied for carbon cycle. Diatoms play an important role in sequestering CO_2 whereas coccolithophores produce CO_2 gas as they precipitate coccoliths made of calcium carbonate. Consequently, they play a significant role in CO_2/O_2 exchange between the ocean and atmosphere and inorganic carbon pump (Holligan, 1992).



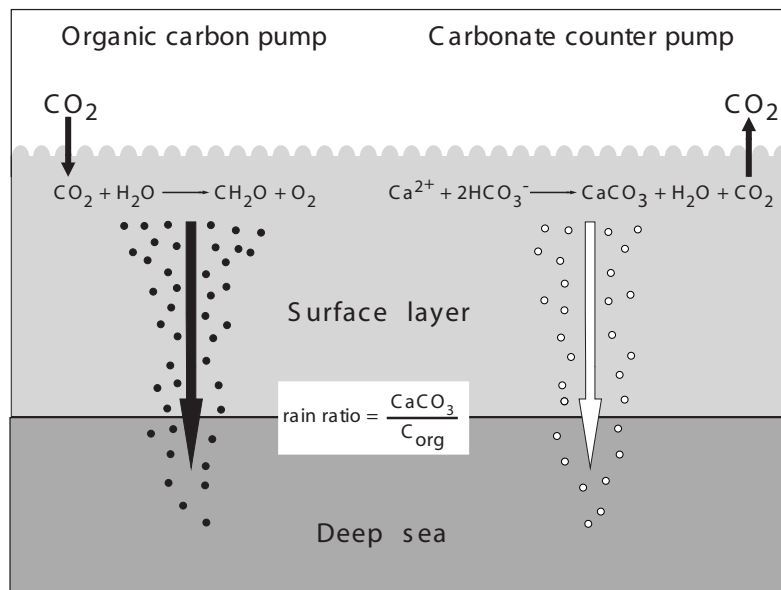


Fig. 1.1. The biological carbon pump (after Rost and Riebesell, 2004).

Calcification of coccolithophores in the ocean is a major source of calcite sediment in the world oceans playing a significant role in the export of calcium carbonate to the deep sea. The valuable knowledge of living assemblages and their occurrence as isolated coccoliths in the surface sediments are potentially used for paleoenvironmental studies and in the paleoceanographic reconstruction of marine sediments. The distribution and ecology of living coccolithophores are governed by water masses and stratification (Jordan and Chamberlain, 1997). Owing to their response to any variation in surface water conditions, these are best suited microfossils to study the long-term climatic signals preserved in the sediment. These coccolithophores have been recognized as proxies of oceanic environment and widely used in paleoclimatological studies. Besides, they are extensively used in the biostratigraphy of marine bottom sediments of late Triassic through Pleistocene (Perch-Nielsen, 1985a, b).

Therefore, the study of coccolithophores from the sediment trap samples is necessary to understand the factors controlling their productivity and settling to the sea floor as they influence the biogeochemical cycling of major elements which in turn influence the life in the oceans. Furthermore, these settling particles are one of the key pathways by which the carbon is removed from the atmosphere and released within the oceans. These coccolithophores are also used as proxies to infer hydrographic conditions. As a part of my comprehensive investigations on extant coccolithophores from the northern Indian Ocean, an attempt is made to relate coccolithophore assemblages with the prevailing oceanographic conditions in the Bay of Bengal. Thus, it would enable to understand the effect of fresh water influx on coccolithophores in the northern Bay and their fluxes away from the fluvial and continental input further south.

1.2 Biogeography of coccolithophores in broader perspective

Coccolithophores, like most other phytoplankton and micro zooplankton groups can be separated into 5 major latitudinal zones:

Subarctic, Temperate (or Transitional), Subtropical (or Central), Tropical (or Equatorial) and Subantarctic (Winter et al., 1994).

a) Subarctic

In coastal regions of Arctic countries where low temperatures and salinities prevail, the only living coccolithophores are those belonging to the *Papposphaeraceae* the partially calcified genera. While, in open ocean, mainly during summer months, *Coccolithus pelagicus* and *Calciopappus caudatus* are the only coccolithophores present.

b) Temperate

Emiliana huxleyi is one of the most dominant species occurring during most part of the year in the temperate region. *Gephyrocapsa muellerae* is common to abundant in upwelling waters of this zone, especially during summer months. Besides, temperate flora is also characterized by other placolith-bearing species such as *Gephyrocapsa oceanica*, *Calcidiscus leptopora*, *Umbilicosphaera sibogae* and *Oolithotus fragilis*.

c) Subtropical

Based on the studies carried out till date, it is inferred that the distribution pattern of coccolithophores show high diversity with vertical zonation characterized by holococcolithophore species such as *Discosphaera tubifera*, *Rhabdosphaera clavigera*, *Umbellosphaera* sp., *Florisphaera profunda*, *Gladiolithus flabellatus* and *Syracosphaera* sp.

d) Tropical

Generally, this region is dominated by placolith-bearing species, particularly, *E. huxleyi*, *C. leptopora*, and *G. oceanica*. *Umbellosphaera* sp., *F. profunda* and *G. flabellatus* also present.

e) Subantarctic

The only coccolithophore living in the subzero polar waters are those belonging to the *Papposphaeraceae* which are partially calcified genera.

The common species found in the coastal waters are species of *Braarudosphaera*, *Cruciplacolithus*, *Hymenomonas*, *Ochrosphaera*, *Pleurochrysis* and *Jomonolithus* and in freshwaters *Hymenomonas roseola*.

In temperate and subpolar zones, nutrients are seasonally replenished in the upper water column resulting in the development of large phytoplankton blooms mainly of diatoms. Thus increasing the settling particles within the upper water column, resulting in the light penetration through depth (Winter et al., 1994). As a consequence of this, species zonation within the photic zone is rather limited. However in the subtropics, nutrient recycling from deep water does not occur resulting in low surface productivity. And also, relatively constant weather conditions allow the upper waters to remain permanently stratified. The Subtropical Zone can be classified into a natural vertical zonation with majority of species confined either to the upper photic zone (0-80 m) or lower photic (120-220 m) zone. The middle of the photic zone (80-120 m) is less distinctive and may incorporate species from either zones.

i) UPPER PHOTIC ZONE (0-80 m)

This zone is characterized by holoccolithophores, *R. clavigera*, *D. tubifera*, *Neosphaera coccolithomorpha*, *Umbellosphaera* sp., *Acanthoica quatrosquina*, *Ceratolithus cristatus*, *Aliaphaera*, *Coronosphaera*, *Syracosphaera*, *Polycrater* and *Cyrtosphaera*.

ii) MIDDLE PHOTIC ZONE (80-120 m)

This zone is not easily distinguished by a characteristic flora but usually contains high abundances of a few species which are also found in the other zones, In particular, *Umbellosphaera tenuis* and *Syracosphaera* sp., and placolith bearing species and few *Anoplosolenia*, *Calciosolenia*, *Alisphaera*, *Coronosphaera* and *Ophiaster*.

iii) LOWER PHOTIC ZONE (120-220 m)

This zone is characterized by the presence of *F. profunda*, *G. flabellatus*, *Hayaster perplexus*, *Algirosphaera quadrucornu*, *Turrilithus*

latericioides, *Syracosphaera anthos*, *Cyclolithus anulus*, *Canistrolithus*, *Vexillarius*, *Gladiolithus* and *O. fragilis*.

1.3 Sedimentation

Sedimentation of coccolithophores is a very unique and interesting process which eventually forms huge deposits of nanno ooze in the deep seas (Fig. 1.2). The mass of a single coccolith is very small (about $8 \times 10^{-6} \mu\text{g}$) with a large surface area (about $32 \mu\text{m}^2$), which results in low settling velocity (about 13.8 cm d^{-1}). Honjo (1976), using the Stoke's relationship for the settling of particles in fluid has shown that an individual coccolith from a coccosphere would take about 100 years to settle unassisted in the open ocean. Thus, their slow sinking rate results in long residence times in the water-column which is subjected to dissolution. Besides, these coccolithophores in the open ocean are under high pressure to grazing by zooplankton which pass through the gut of these organisms with or without mechanical or chemical effect on coccoliths (calcite plates). Fecal pellets and other oceanic macroaggregates are the main carriers for the rapid vertical transport of the majority of coccoliths through under saturated waters to the sea-floor (Honjo, 1975, 1976, 1980; Honjo and Roman, 1978). Coccolithophores are generally well preserved within these rapid settling vehicles (Honjo, 1975; Knappertsbusch and Brummer, 1995) and found below the calcite saturation depth with little or no effect of selective dissolution. Honjo (1976) observed that the free coccolith and coccospheres are replenished at all depths by descending fecal pellets. Once the contents of these host fecal pellets or macroaggregates are spilled, or released, their rate of descent decreases considerably and are exposed to the under saturated deep water (Honjo, 1975). The two major causes of a strong alteration of settling assemblages are biological breakage caused by grazing, re-suspension and lateral advection within an extensive bottom nepheloid layer overprinting the vertically settling coccolithophore assemblages (Andrulleit, 2000).

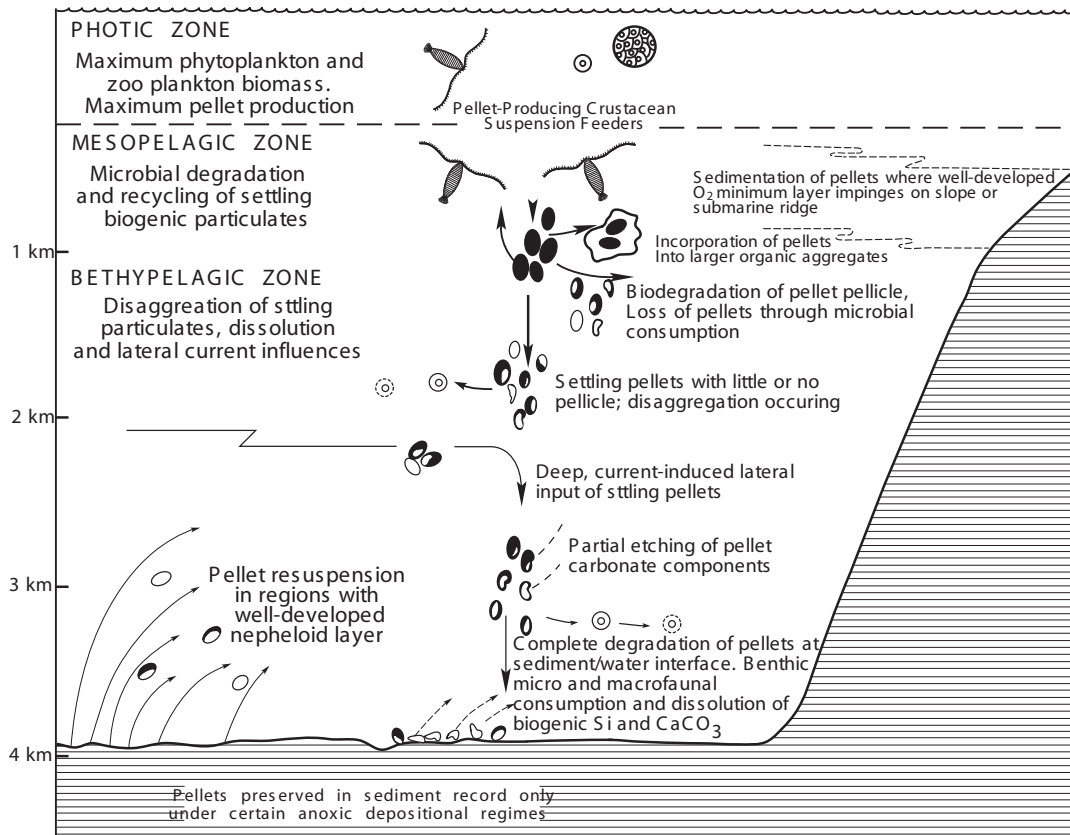


Fig. 1.2. A model for coccolithophore sedimentation (after Steinmetz, 1994).

1.4 Sediment trap studies in the Indian Ocean

The sediment trap studies in the Indian Ocean, particularly in the northern Indian Ocean, which includes Arabian Sea and Bay of Bengal were initiated in 1986 under the Indo-German bilateral program between the National Institute of Oceanography, Goa and the Institute of Biogeochemistry and Marine Chemistry, Hamburg University, Germany. Studies carried out under this program were the first to show the link between monsoons and sedimentation of particles including carbon from the ocean surface to the deep sea, much needed information to validate the use of sediment record to decipher past monsoon and to re-construct paleoceanography.

Ever since, the sediment trap experiments were initiated to carry out biogeochemical processes in the northern Indian Ocean, large numbers of scientific papers have been published highlighting the implication of particle fluxes on the prevailing reversing monsoon system in the northern Indian Ocean. Some of the notable contributions are by Nair et al. (1989) and Ittekkot et al. (1991) who have for the first time reported the sediment trap results of the particle fluxes from both the Arabian Sea and Bay of Bengal.

1.5 Study of living coccolithophores from the Indian Ocean

Although several studies on coccolithophores have been carried out from the Indian Ocean they are all largely restricted to the marine sediments (Norris, 1971; Martini & Müller, 1972; Čepeš, 1973; Bukry, 1974; Boudreaux, 1974; Guptha, 1974, 1976, 1979, 1983, 1985, 1986; Guptha and Nigam, 1984; Houghton and Guptha, 1991; Andrulait and Rogalla, 2002).

However, the first ever study on the extant coccolithophores (nannoplankton) from the Indian Ocean (Arabian Sea) was carried out by Norris (1971). Later the study of living coccolithophores was revived again after a lapse of about a decade by Norris (1983, 1984, 1985), Woellner et al. (1988), Kleijne et al. (1989) and Zeltner (1998). Kleijne (1991, 1992) has documented the extant coccolithophores in the Arabian Sea samples collected in a traverse from the southeastern Indian Ocean to the Gulf of Aden and Red Sea. Guptha et al. (1995) studied coccolithophores from the euphotic

zone in the Arabian Sea during the tail end of summer monsoon where the low fertility of water during September-October caused the abundance of *E. huxleyi* and *U. irregularis*.

Andruleit et al. (2000) investigated the coccolithophores from four sediment traps located in the northeastern Arabian Sea off Pakistan. The coccolith fluxes were characterized by a strong seasonality with high fluxes during the early SW monsoon (summer) and early northeast (NE) monsoon (winter). *G. oceanica*, *F. profunda* and *E. huxleyi* were the dominant species constituting about 70% of the total assemblages. *Umbellosphaera* sp. showed a high relative abundance in the intermonsoon showing its preference for warm and oligotrophic waters. It was inferred that the productivity in the surface waters was a resultant of the upwelling along the Oman coast which advected nutrient rich upwelled waters to the trap location. Whereas during NE monsoon it was attributed to local injection of nutrient-rich deep water into the surface water due to sea-surface cooling leading to convection.

Broerse et al. (2000a) studied the coccolithophores collected in a sediment trap off Somalia (northwestern Indian Ocean) which responded rapidly to the SW and NE monsoons with variation in productivity, species composition, coccolith: coccosphere ratio and CaCO₃ productions. The deep-photic zone species such as *F. profunda* and *G. flabellatus* were dominant in the early SW monsoon when coastal upwelled waters advected by a gyre, towards the trap location. *E. huxleyi* and *G. oceanica* dominated the assemblage during the peak of SW monsoon, whereas most of the other coccolithophore species showed maximum relative abundance during upwelling relaxation when the coccolithophore fluxes began to decrease. During the intermonsoon periods when the surface waters were stratified and, nutrient-depleted coincided with decreased fluxes and increased oligotrophic indicator species such as *U. irregularis*. While, during NE monsoon coccolithophores displayed a rapid increase in its fluxes in response to a moderate wind-induced entrainment of nutrients.

Andruleit et al. (2003) studied the living flora from the northern Arabian Sea during the fag end of SW monsoon. They reported that coccolithophore

communities reflected the local oceanographic conditions and seemed to be more dependent on a mixed layer depth and nutrient availability than the temperature and salinity variations.

Recently, Schiebel et al. (2004) studied the distribution of diatoms, coccolithophores and planktic foraminifers during SW monsoon in the Arabian Sea. They reported lower coccolithophore cell numbers as well as diversity in the upwelling area close to the Oman coast and increased cell concentration towards the open ocean where low nutrients and increased stratification of the upper water column prevails.

Guptha et al. (2004) in their study on coccolithophores from the photic zone of the equatorial Indian Ocean reported the occurrence of dissolution of coccolithophores. Guptha et al. (2005) studied the living coccolithophores from the Equatorial Indian Ocean along 93°E transect during NE monsoon. The floral assemblage showed higher abundance of *U. irregularis* indicating the prevalence of oligotrophic conditions in the upper mixed layer (~50 m thick). Besides, increased abundance of *F. profunda* at 4°S suggested injection of nutrients by upwelling into the shallow mixed layer depths.

Very recently, Mergulhao et al. (2006) studied the temporal variation of coccolithophore fluxes from the Central Arabian Sea Trap. The total coccolithophore fluxes showed a distinct seasonality with higher fluxes occurring during the NE monsoon and lower fluxes during the spring intermonsoon. The higher fluxes were attributed to the increased primary production in the central Arabian Sea due to southward extension of nutrients rich water from the NE Arabian Sea by the prevailing surface currents.

Despite the fact that a beginning has been made to study extant coccolithophores from the sediment traps in the northern Indian Ocean by Zeltner (1998), Andruleit et al. (2000), Broerse et al. (2000a), and Mergulhao et al. (2006), not much significant progress has been made yet. Therefore, it was necessary for me to undertake a detailed investigation to improve the understanding of these microplankton as proxy indicators, which eventually help in the reconstructions of long-term monsoonal and climate change.

1.6 Study of living coccolithophores: A world perspective

The study of modern coccolithophores was initiated more than a century ago, by Murray (1885) and Murray and Blackman (1898) followed by Gran (1912) and Lohmann (1920) who recognized the diversity of coccolithophores from the central and northern Atlantic Ocean. Later, McIntyre and Bé (1967) carried out a quantitative study on the distribution of coccolithophores in the Atlantic waters, however no quantitative data was available. They have also identified four floral zones *viz*: tropical, subtropical, transitional, subarctic and subantarctic. Gaarder (1971) regarded Atlantic Ocean as having the richest coccolithophore flora. Subsequently, Okada and McIntyre (1979) studied the seasonal and vertical distribution of coccolithophores from 540 water samples in the North Atlantic Ocean. This study enabled them to revise their earlier classification and further revealed that the coccolithophore abundance decreased in the northern stations during winter months and during summer months in the southern stations. Jordan (1988) studied coccolithophore community from North Atlantic Ocean. Later, Giraudeau et al. (1993), Samtleben et al. (1995a), Baumann et al. (1999) and Kinkel et al. (2000) studied the distribution of living coccolithophores flora from the Atlantic Ocean.

Besides, extensive studies on coccolithophores have also been carried out from the Norwegian Seas by Braarud et al. (1953), Smayda (1958), Gran (1929) and Paasche (1960) and identified a number of floral zones based on phytoplankton composition and related them to various water masses. Samtleben and Schröder (1992), Samtleben et al. (1995b) and Baumann et al. (2000) also studied living coccolithophore communities and their assemblages in the sediment from the Norwegian-Greenland Sea.

Gaarder and Hasle (1971) and Hulburt (1968) studied the coccolithophores from the Caribbean and Gulf of Mexico. Lohmann (1902) published a monograph on coccolithophores in the Mediterranean which gave inspiration for the later workers. After a lapse of about three decades, Schiller (1930) published a monograph on coccolithophores from the Adriatic Sea. Later, Kamptner (1937, 1941, 1944) made a significant contribution to

coccolithophores research from the other parts of the Mediterranean. Later Knappertsbusch (1990) and Kleijne (1991) studied the quantitative distribution of coccolithophores.

From the Pacific Ocean, most significant and notable contributions were made by Marshall (1933), Gran (1929), Hasle (1959, 1960) and Norris, (1961). However, a decade later McIntyre et al. (1970) studied the biogeography of coccolithophores from the north and south Pacific, followed by major quantitative studies carried out by Okada and Honjo (1973), Honjo and Okada (1974) and Nishida (1979). Recently, Ziveri et al. (1995a), Hagino et al. (2000) and Takahashi and Okada (2000) studied the living coccolithophores from the Pacific Ocean.

Besides, there are several studies carried out on coccolithophore fluxes from the other regions such as Norwegian Sea (Samtleben and Bickert, 1990), San Pedro Basin (Ziveri et al., 1995b), northeastern central tropical Pacific Ocean (Broerse, 2000), northeastern Atlantic Ocean (Broerse et al., 2000b), Guaymas Basin (Ziveri and Thunell, 2000), equatorial west Pacific Ocean (Tanaka and Kawahata, 2001), Okhotsk Sea (Broerse et al., 2000c), north Atlantic Ocean (Haidar et al., 2000), northeastern Atlantic Ocean (Ziveri et al., 2000) and central Greenland Sea (Andruleit, 2000).

1.7 Objectives

The major goals of the present study are:

- 1) To generate basic data on living coccolithophores from the time series sediment traps in the least explored Bay of Bengal which would be of immense use in understanding the various biogeochemical processes operating and in the re-construction of the paleoceanographic record of Quaternary sediment.
- 2) To infer spatial and temporal distribution of coccolithophore fluxes in the monsoon dominated Bay of Bengal and their implication on hydrography.
- 3) To estimate coccolithophore-CaCO₃ (nanno ooze) contribution to the annual total carbonate flux in the Bay of Bengal.

The Bay of Bengal receives a large influx of freshwater during SW monsoon leading to a strong stratification in the near-surface layer and also the seasonally reversing monsoon winds influence the Bay of Bengal circulation pattern significantly affecting the general hydrography of the surface waters. Therefore an attempt has been made in the present investigation to address the relationship of coccolithophore settling assemblages in the water column with the prevailing oceanographic conditions in the euphotic zone.

Besides, in view of the fact that the coccolithophores are abundant and widely distributed component of the marine phytoplankton in the oceans, the knowledge on them and their response to hydrographical changes would be of immense use in understanding the relationship between living communities and their fossil counterparts which would vary from region to region with specific environmental settling.