

Bay of Bengal Process Studies

(BOBPS)

**Final Report Submitted to the
Department of Ocean Development
New Delhi**

Prepared by

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CONTENTS

Acknowledgements	4
1. Executive Summary	5
2. The Bay of Bengal Process Studies (BOBPS) Programme	7
2.1 Introduction	7
2.2 Genesis	7
2.3 Objectives	8
2.4 Programme duration and coordinators	8
2.5 Sub-projects under BOBPS	9
2.6. Funding	10
2.7 Cruise track and details	11
2.8. Parameters measured	12
2.9 Meetings and events	13
3. Physical Oceanography programme	
Response of the upper ocean to atmospheric forcing in the Bay of Bengal on seasonal and inter-annual scale	14
4. Biological Programme	
4.1 Biological productivity characteristics in the Bay of Bengal	30
4.2 New Production studies	50
5. Biogeochemistry Programme	
5.1 Biogeochemical cycling of Carbon & Nitrogen in the Bay of Bengal	55
5.2 Biochemical cycling of Carbohydrates, Amino acids and Amino sugars	72

6. Burial-fluxes	
Burial-fluxes and paleo-fluxes of carbon in the Bay of Bengal	98
7. Data Management	110
8. Modeling	
Modeling of the biogeochemical cycles in the Bay of Bengal	114
9. Atmospheric Aerosols Study	135
10. Summary and Conclusions	140
11. Papers published	141

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Finally, BOBPS community gratefully acknowledges the financial support and support in terms of ship facility onboard ORV Sagar Kanaya and FORV Sagar Sampada provided by the Department of Ocean development, Government of India, New Delhi.

1. Executive Summary

The Bay of Bengal Process Studies (BOBPS) was conceived in early 1997 as a sequel to the JGOFS (Joint Global Ocean Flux Study) India - Arabian Sea Process Study. Soon after the completion of the JGOFS field experiments in the Arabian Sea in February 1997 a consolidated national BOBPS programme was submitted to Department of Ocean Development (DOD), New Delhi in February 1999.

The overall objectives of the Bay of Bengal Process Studies were:

1. Spatial and temporal variations in physical, chemical and biological properties (i.e, temperature, salinity, density, wind, pressure, SST, air temperature, humidity, nutrients, primary productivity, abundance and annual cycle of bacteria, micro- & meso-zooplankton, POC) and the effect of various forcing such as fresh water, suspended discharge, evaporation, precipitation etc. in contributing to this. The Bay of Bengal is known for its cyclones. These transients would have significant effects on the distribution of chemical and biological properties and biogeochemical cycling of carbon. Attempts are being made to sample the water column after such events to assess their significance.
2. Seasonal and inter-annual variability in the overall CO₂ air-sea exchange balance in the Bay of Bengal.
3. The role of remote forcing in the spatio-temporal variability of the water column in terms of nutrients and productivity.

For achieving the above objectives 9 sub-projects were approved and funded by DOD by the administrative approval on 19 October 2000 for a total budget of Rs. 146.93 lakhs. The institutions involved were National Institute of Oceanography (NIO), Goa, Physical Research Laboratory (PRL), Ahmedabad, Centre for Mathematical Modelling and Computer Simulation (C-MMACS), Bangalore and Goa University (GU), Goa.

In all 4 cruises were conducted during 2001 and 2006. Out of this, three were on board ORV Sagar Kanya during summer 2001, fall intermonsoon 2002, spring intermonsoon 2003 and one onboard FORV Sagar Sampada during winter 2005. In all the cruises sampling were carried out at the same location so as to decipher the seasonal cycle. In each of the cruise, 24 CTD stations - 14 along the 88°E and 10 were along the western boundary - and 9 primary productivity (PP) stations - 5 were along 88°E, and 4 were along western boundary - were covered. In all 35 parameters were measured.

Several new insights are emerging out of the BOBPS data analysis. We now understand why Bay of Bengal is a biologically low productive basin. This is largely due to the strong stratification driven by the immense fresh water flux and in parts due to the shallow euphotic zone especially in the northern Bay due to immense suspended sediment load. The role of sub-surface cold-core eddies in supporting enhanced biological production due to up-ward eddy-pumping of nutrients across the halocline is clearly seen. This to some extent will address the issue of comparable down-ward particle (organic) flux in the Bay of Bengal and the Arabian Sea despite contrasting surface chlorophyll concentrations and production. Existence of large bacterial abundance, crucial for microheterotrophs, explains why the mesozooplankton biomass may be decoupled with chlorophyll and primary production. Contrary to the conventional belief that the Bay of Bengal may be asink for atmospheric CO₂, the pCO₂ and TCO₂ measurements indicate that except in the northern Bay during summer and fall intermonsoon, the Bay of Bengal is a minor source of CO₂ to atmosphere. In the absence of any strong upwelling region in the Bay of Bengal this appers to be driven by eddy-pumping of CO₂-rich subsurface waters to the upper layers which then diffuses under the action of prevailing winds.

2. Bay of Bengal Process Studies (BOBPS) Programme

2.1 Introduction

The Bay of Bengal is characteristically different from the other tropical basins of the world. This is partly due to its limited northern extent and the monsoonal wind forcing which reverses semi-annually. Although the geographical setting of the Bay of Bengal is very similar to the Arabian Sea, the Bay appears to be vastly different from the Arabian Sea in physical, chemical and biological features (see below). The prime reason for this is the immense quantities of fresh water runoff ($\sim 1.5 \times 10^{12} \text{ m}^3$ per year) and the associated sediment load (billions of tonnes) it brings in to the basin. The obvious question is what happens to the nutrients in this tonnage and why is it that the Bay is reportedly (and apparently) less productive in comparison to its western counterpart the Arabian Sea? In addition to this, the occasional cyclones during May and October are expected to offset the heat and buoyancy fluxes dramatically over very short span of time, triggering associated changes in the water column chemistry and biology. We do not yet understand the magnitude and spatio-temporal scales associated with such processes. Though the International Indian Ocean Expedition (IIOE) during 1960-65 investigated multiple aspects of the oceanography of Indian Ocean amassing volumes of data, all collected data could not be synthesized very effectively. This is clearly evident from the experience of Krey and Babenard (1976) had while preparing the Plankton Atlas for the Indian Ocean. To highlight the difficulties with the analyses of IIOE data on phytoplankton and primary production, it may be appropriate to quote Babenard: “The lack of systematic survey for the entire ocean and necessity to combine data from many years, as well as variability in time and heterogeneity in space made the preparation of the Atlas rather troublesome”. In addition, the number of cruises that were undertaken for studying Bay of Bengal during the IIOE was very few. As an example, for chlorophyll *a* measurements there were less than 270 samples for May-October and less than 450 samples for November-April from the Bay during the entire period of IIOE. In spite of the post IIOE efforts by India (NIO) as well as other countries, the Bay of Bengal remains under-sampled and least understood. The fact is that the Bay remains an enigma and the Bay of Bengal Process Studies (BOBPS) Programme aims at unraveling some of the mysteries.

2.2 Genesis

The Indian Joint Global Ocean Flux Study (JGOFS) programme was conceived in 1991 at a meeting at the National Institute of Oceanography, Goa and subsequently a Steering Committee was constituted by the Department of Ocean Development (DOD), Government of India, New Delhi to generate, monitor and implement the programmes of JGOFS (India). In the steering committee meeting it was agreed upon that “the broad goals of JGOFS (India) would be to obtain a better understanding of the carbon cycle and processes regulating it in the adjoining seas of India, **the Arabian Sea and the Bay of Bengal**”. A consolidated national JGOFS proposal was submitted to DOD in January 1993 for the first phase of the programme on the Arabian Sea, which was subsequently approved by the Committee, financially supported by the DOD, and implemented by scientists from four national agencies, National Institute of Oceanography (NIO), Physical Research Laboratory (PRL), National Chemical Laboratory (NCL) and Centre for Mathematical Modelling and Computer Simulations (C-MMACS) during 1994-2000.

Bay of Bengal Process Studies (BOBPS), a sequel to the JGOFS (Joint Global Ocean Flux Study) India - Arabian Sea Process Study, has been conceived in early 1997 soon after the completion of the field experiments in the Arabian Sea in February. The scientific rationale for extending the studies to the Bay of Bengal was discussed during the last Steering Committee meeting of JGOFS (India). The Chairman, Prof. V.K. Gaur suggested (vide letter No. DOD/22/IGBP/1/91-DDIII dated 20.2.97) that (1) the PIs formulate a project highlighting the major questions to be addressed in their studies, their anticipated results and budget needs and (2) to convene a National Brain Storming Meeting to evolve a suitable proposal for studies of biogeochemical process in the Bay of Bengal. Subsequently, a brain storming session was held at Goa on 20-21 November 1997 to draw up a National Science Plan for BOBPS in which scientists from various national agencies and universities participated. It took almost one year to prepare research proposals by various agencies and submit them to the Department of Ocean Development (DOD) for funding. Based on the recommendations by experts a revised proposal, limiting the number of investigations and pruning the budget, was submitted to DOD in February 1999.

2.3 Objectives

Overall objectives of the Bay of Bengal Process Studies are:

4. Spatial and temporal variations in physical, chemical and biological properties (i.e, temperature, salinity, density, wind, pressure, SST, air temperature, humidity, nutrients, primary productivity, abundance and annual cycle of bacteria, micro- & meso-zooplankton, POC) and the effect of various forcing such as fresh water, suspended discharge, evaporation, precipitation etc. in contributing to this. The Bay of Bengal is known for its cyclones. These transients would have significant effects on the distribution of chemical and biological properties and biogeochemical cycling of carbon. Attempts are being made to sample the water column after such events to assess their significance.
5. Seasonal and inter-annual variability in the overall CO₂ air-sea exchange balance in the Bay of Bengal.
6. The role of remote forcing in the spatio-temporal variability of the water column in terms of nutrients and productivity.

2.4 Programme duration and coordinators

The programme implementation commenced with the administrative approval on 19 October 2000 and terminated on 31 March 2006.

Dr. M. Madhuratap, NIO was the National Coordinator and Dr. S. Prasanna Kumar, NIO was the Co-coordinator till 7 January 2004.

After the sad and sudden demise of Dr. Madhuratap, on 7 January 2004, Dr. Prasanna Kumar was nominated as the National Coordinator.

The following 9 sub-projects were approved and funded (administrative approval) under BOBPS project in 19 October 2000.

2.5 Sub-projects under BOBPS

Sub-project Number	Title of the sub-project	Principal Investigator (PI)
1	Response of the upper ocean to atmospheric forcing in the Bay of Bengal on seasonal and inter-annual scale	Dr. S. Prasanna Kumar NIO, Goa
2	Biological productivity characteristics in the Bay of Bengal	Late Dr. M. Madhupratap NIO, Goa (till 7 January 2004) Dr. Ramaiah NIO, Goa (from 8 January 2004)
3	Biogeochemical cycling of Carbon & Nitrogen in the Bay of Bengal	Dr. S.N. d Souza NIO, Goa (till 2003) Dr. Sugandhini Sardesai NIO, Goa (from 2004)
4	Biochemical cycling of Carbohydrates, Amino acids and Amino sugars	Dr. N. Bhosle NIO, Goa
5	Burial-fluxes and paleo-fluxes of carbon in the Bay of Bengal	Dr. V. Ramaswamy NIO, Goa
6	Bay of Bengal Process Studies – Data Management	Mr. J. Sarupriya NIO, Goa
7	Biogeochemical study of atmospheric aerosols & radionuclides	Dr. M.M. Sarin PRL, Ahmedabad
8	Modeling of the biogeochemical cycles in the Bay of Bengal	Dr. M.K. Sharada C-MMACS, Bangalore
9	Biological productivity characteristics in the Bay of Bengal	Dr. Usha Muraleedharan Goa University, Goa

2.6. Funding

The total outlay of the project finally sanctioned from Department of Ocean Development (DOD) vide OM No. DOD/22/IGBP/1/98 dated 19th October 2000 was Rs. 146.93 lakhs.

The following table gives a summary of the amount sanctioned and disbursed to various sub-projects for the execution of the BOBPS project:

Title of the sub-project	Total Sanctioned Project Cost (in lakhs)	Amount received so far (in lakhs)
Response of the upper ocean to atmospheric forcing in the Bay of Bengal on seasonal and inter-annual scale (NIO)	21.95	17.981
Biological productivity characteristics in the Bay of Bengal (NIO)	24.22	21.827
Biogeochemical cycling of Carbon & Nitrogen in the Bay of Bengal (NIO)	23.96	21.660
Biochemical cycling of Carbohydrates, Amino acids and Amino sugars (NIO)	8.52	7.785
Burial-fluxes and paleo-fluxes of carbon in the Bay of Bengal (NIO)	20.92	13.390
Bay of Bengal Process Studies – Data Management (NIO)	4.57	3.639
Biogeochemical study of atmospheric aerosols & radionuclides (PRL)	20.84	3.63
Modeling of the biogeochemical cycles in the Bay of Bengal (C-MMACS)	10.0	9.79
Biological productivity characteristics in the Bay of Bengal (GU)	11.97	10.37
Total	146.93	110.252

2.7. Cruise track and details

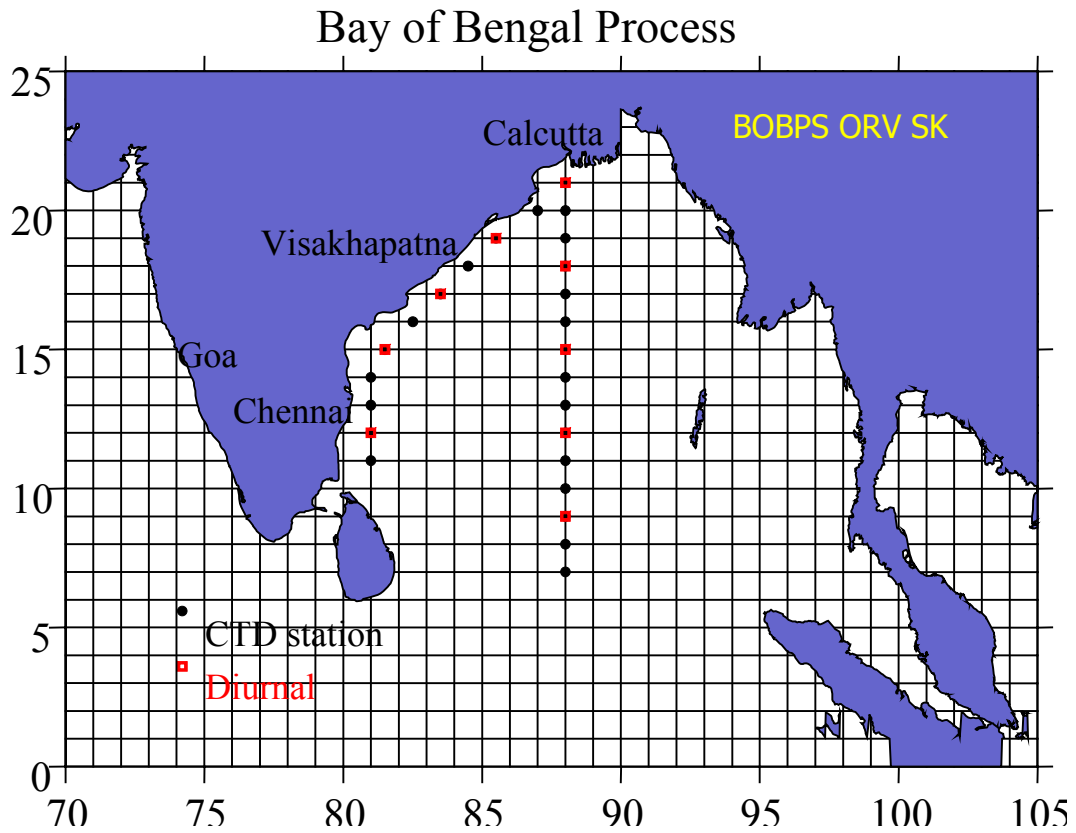


Figure 1 Location map showing the location of *in situ* sampling stations. Dark circles are the CTD stations while red filled squares are the PP stations where diurnal biological sampling were carried out in addition to the *in situ* incubation.

In all 4 cruises were conducted during 2001 and 2006, three on board ORV Sagar Kanya (SK) and one onboard FORV Sagar Sampada (SS). Following are the details.

Serial Number	Cruise Number	Sampling period	Representative season
1	SK-166	6 July – 2 August 2001	Summer monsoon
2	SK-182	14 September – 12 October 2002	Fall intermonsoon
3	SK-191	10 April – 10 May 2003	Spring intermonsoon
4	SS-240	25 November 2005 – 7 January 2006	Winter monsoon

In all the cruises sampling were carried out at the same location so as to decipher the seasonal cycle. In each of the cruise, 24 CTD stations and 9 primary productivity (PP) stations were covered. Out of the 24 CTD stations 14 were open ocean stations along the 88°E and 10 were along the western boundary. Similarly, out of the 9 PP stations, 5 were along 88°E, and 4 were along western boundary (Fig.1)

2.8. Parameters measured

1. Temperature profile
2. Salinity profile
3. Fluorescence profile
4. Sea surface temperature (SST)
5. Wind speed and direction
6. Air temperature and wet bulb temperature
7. Atmospheric pressure
8. Current speed and direction
9. Chlorophyll *a*
10. Primary production rate
11. ¹⁵N based new production
12. Phytoplankton species composition
13. Mesozooplankton
14. Microzooplankton
15. Microzooplankton grazing
16. Bacterial abundance
17. Bacterial production rate
18. Direct viable counts
19. Enumeration of colony forming units of bacteria
20. Enumeration of Mercury Resistant Bacteria
21. TEP counts and concentration
22. POC/PON
23. Dissolved oxygen
24. TCO₂
25. pH
26. Alkalinity
27. DMS & DMSP
28. Nutrients (Nitrate, Silicate, Phosphate)
29. TOC
30. Amino Acids

31. Carbohydrates
32. Lignin
33. Amino sugars
34. SPM
35. Molecular Fractionation

2.9. Meetings and events

1. One-day workshop held at NIO, Goa on 20 December 2001 to discuss the results obtained the summer cruise of ORV Sagar Kanya, SK-166.
2. One-day workshop held at NIO, Goa on 18 March 2003 to discuss of results obtained from the fall intermonsoon cruise of ORV Sagar Kanya, SK-182.
3. Monitoring committee meeting of Bay of Bengal Process Studies (BOBPS) held at DOD – Delhi on 30th December 2003.
4. One-day workshop held at NIO, Goa on 16 June 2004 to discuss the results obtained the spring intermonsoon cruise of ORV Sagar Kanya, SK-191.
5. Final meeting of Bay of Bengal Process Studies (BOBPS) held at NIO, Goa on 25 January 2006 to discuss the results obtained so far from 4 cruises during summer 2001, fall intermonsoon 2002, spring intermonsoon 2003 and winter monsoon 2005.

3. Physical Oceanography Programme

Response of the upper ocean to atmospheric forcing in the Bay of Bengal on seasonal and inter-annual scale

Participants:

National Institute of Oceanography, Dona Paula, Goa.

S. Prasanna Kumar **Principal Investigator**
P.M. Muraleedharan
G. Nampoothiri
A. Almeida
Nuncio Murukesh
Jayu Narvekar
Deepthi M.
Gaurish Salgaonkar

Objectives

The primary objectives of the proposed study is to address the role of physical processes in the overall biogeochemistry of the Bay of Bengal by determining

- (1) How far is the physical forcing coupled with biological processes and
- (2) To what extent physical forcing controls the carbon cycling in the Bay

This could be achieved by studying the response and spatio-temporal variability of the Bay of Bengal to (1) the monsoonal forcing, (2) fresh water forcing, and (3) role of cyclones in controlling the dynamics of the upper ocean and its coupling to the changes in water column chemistry and biology.

Introduction

It is well known that the biological production in warm tropical waters is controlled by the availability of nutrients and physical process sets the stage for making the nutrients available to the upper layers. Being a tropical basin, the biological production in the Bay of Bengal is expected to be nutrient limited and hence carbon cycling, to a large extent, must be modulated by the physical processes. The circulation and hydrography of the Bay of Bengal is complex due to the interplay of semi-annually reversing monsoonal winds and the associated heat and freshwater fluxes. Apart from this, the inflow of warm high saline waters of the Arabian Sea, the Persian Gulf and the Red Sea origin and a number of synoptic disturbances (cyclones) originating during both pre-monsoon (May) and post-monsoon (October) period also affects the upper ocean dynamics. It is generally known that cyclones are capable of inducing rapid changes in the heat and buoyancy fluxes over very short span of time (few days to weeks), but the magnitude of such processes is unknown. Neither do we fully understand the upper ocean variability in the seasonal and inter-annual time scales. Conventional hydrographic surveys for the past few decades after the International Indian Ocean Expedition (IIOE 1960-65) generated considerable amount of information regarding the hydrographic characteristics of the Bay of Bengal and to some extent the general circulation (Varkey *et al.*, 1996, Schott *et al.*, 2001; Shankar *et al.*, 2002 and the references thereof). Though there exists a broad understanding about the hydrography and general circulation of the Bay of Bengal, various aspects of circulation and mixed layer dynamics on a seasonal and inter-annual time scale is yet to be understood. Recent attempts to model the circulation in the Bay of Bengal (Potemra, 1991, Yu *et al.*, 1991; Perigaud and Delecluse, 1993; Vinaychandran *et al.*, 1996; McCreary *et al.*, 1996; Shankar *et al.*, 1996) and Indian Ocean (McCreary *et al.*, 1993) suggested the role of planetary (Kelvin and Rossby) waves in influencing the circulation in the Bay of Bengal. These model studies showed that the low frequency waves on encountering a boundary, such as the eastern Bay of Bengal, propagate part of their energy as coastally trapped Kelvin wave along the eastern periphery, and part of the energy as westward propagating Rossby waves into the Bay of Bengal. This has been corroborated by Prasanna Kumar and Unnikrishnan (1995) and Unnikrishnan *et al.* (1997) based on the temperature climatology and altimeter data (Prasanna Kumar *et al.*, 1996). However, the magnitude of the changes that these low frequency waves would induce in the upper oceans and the implications to water column chemistry and biology is presently not known. Another gray area is stratification associated with the fresh water influx. What is the role of stratification in controlling vertical and horizontal advection? How does this affect the de-gassing in the Bay of Bengal? How strong is the coastal upwelling in terms of nutrient supply to the upper ocean and biological production? Is the winter cooling process active in the Bay of Bengal? If so, does it

trigger winter convection and biological bloom? Does advective process (from western and eastern boundaries) play a major role in fertilizing the Bay of Bengal. What are the magnitudes of the mixed layer changes associated with cyclones and how do they affect the biological production and Carbon flux? Do cyclones act as a switch, which could reset the seasonal or inter-annual anomalies? In summary, how strongly is the biological process coupled to physical forcing? Through this project we envisage to address these questions.

Method

To understand the surface and sub-surface expression of the upper ocean response to atmospheric forcing, *in situ* measurements (hydrographic data) along with satellite data on sea surface height (TOPEX/POSEIDON altimeter), sea surface temperature (AVHRR), and ocean color were used.

Measurements

1. Vertical profiles of (1) salinity and (2) temperature were measured using CTD system at a spatial resolution of one degree.
2. Surface meteorological parameters such as
 - (1) Air temperature
 - (2) Wet bulb temperature
 - (3) Wind speed & direction
 - (4) Pressure

were measured using shipborne automatic weather station as well as using hand held Met-Kit at station. In addition, the sea surface temperature (SST) will be measured using a bucket thermometer at every CTD stations. Sea surface salinity (SSS) as well as SST was also recorded using ship-board digital thermo-salinograph along the ship-track.

3. Upper Ocean currents were measured along the ship-track using shipborne ADCP.

Results

Summer monsoon (July-August 2001)

Surface meteorology

Along the open ocean transect (88°E), the wind speed decreased from 8 m/s to 5 m/s from 8°N to 11°N and then showed an increasing trend towards 20°N attaining a value of about 12 m/s (Fig. 1 top left). The surface pressure decreased from 1013 mb at 7°N to 1003 mb at 20°N (Fig. 1 middle left).

Air temperature on an average was 29°C from 7°N to 12°N and then fluctuated between 28°C to 29°C from 12 to 16°N and then onwards remained 29°C till 20°N (Fig. 1 bottom left). Along the coastal transect wind speeds fluctuated between 2 m/s to 10 m/s (Fig. 1 top right). As in the case of Open Ocean, the pressure along the coastal transect also showed a decreasing trend from 1010 mb to 1003 mb (Fig. 1 middle right). Air temperature decreased from about 29°C at 11°N to 26°C

at 12°N and then showed a sharp increase up to little more than 30°C at 14°N and then showed a steady decrease till 20°N (Fig.1 bottom right).

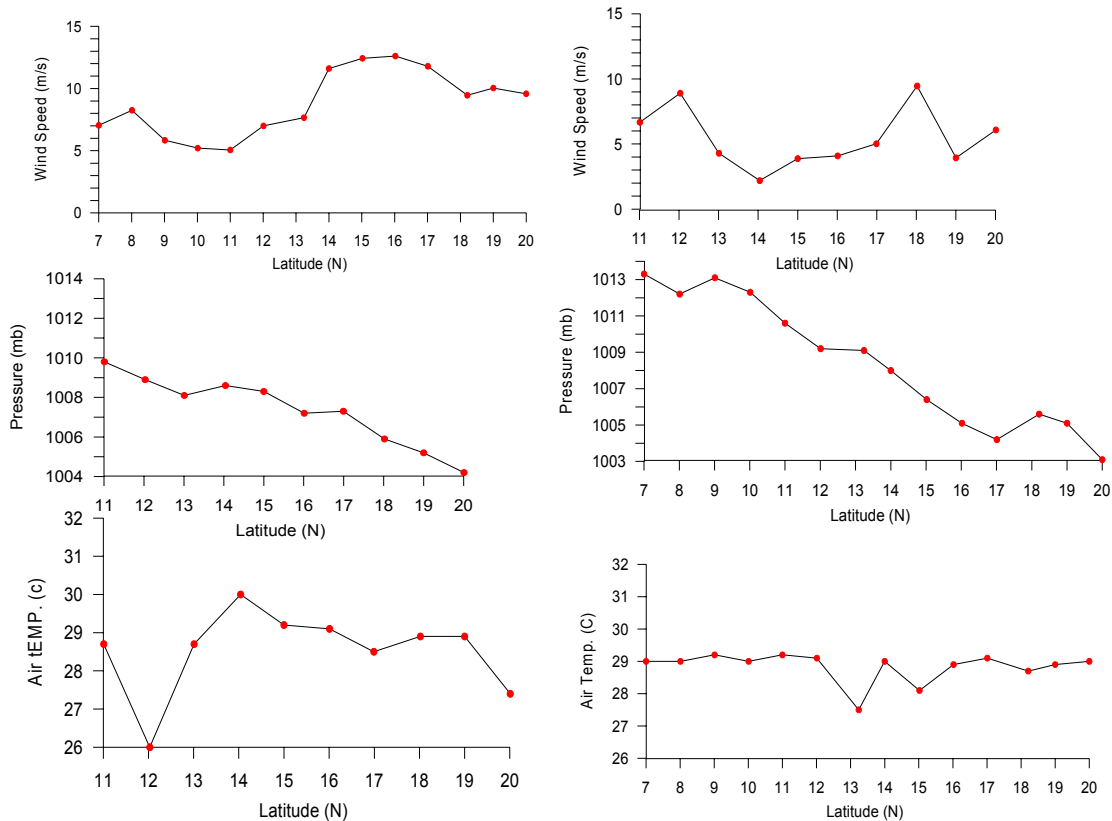


Fig.1 Latitudinal variation of (top) wind speed (middle) atmospheric pressure (bottom) air temperature along open ocean (88°E, left) and coastal (right) transects

Thermal structure

The sea surface temperature (SST) along the open ocean transect (88°E) was on an average 28.4°C between 7°N and 9°N and increased to 29.5°C at 11°N and then showed a decrease from 11°N to 20°N (SST variations not presented). The mixed layer depth (MLD, defined as the depth at which the sigma-t value exceeds surface sigma-t value by 0.2) was about 60m deep at 7°N, which decreased to 15m at 8°N and then was in excess of 50 m at 12°N but shoaled under the influence of increasing freshening more or less gradually to less than 4m at 20°N

The vertical thermal structure in the upper 300 m showed oscillation within the thermocline (Fig.2 left). An upheaval of isotherms was noticed between 7°N and 11°N while north of it the isotherms showed a gradual shoaling towards 20°N. In the former case, the 28°C isotherm shoaled from 80m to 20m and thus the upper thermocline showed a vertical displacement of about 60m, which tapered off towards the lower thermocline. This was clearly a signature of a subsurface cold core eddy, seen below 15m depth, which depressed the ambient temperature at 60m (27°C) by about 5°C. Below 300m, the thermal structure did not show any special features.

Coastal SSTs were on an average 28.9°C and were higher than those at the open ocean stations of the corresponding latitude. MLD, which was 25m at 11°N shoaled northwards to almost imperceptible levels

The thermal structure in the upper 300m along the coastal section also exhibited oscillations within the thermocline (Fig. 2 right) as was the case with the open ocean transect. A noteworthy feature was, again, an uplifting of isotherms centered at 17°N. The 28°C isotherm shoaled from 60m to 10m. This vertical displacement of about 50m in the upper thermocline depressed the ambient temperature by about 5°C. (Fig.2 right panel).

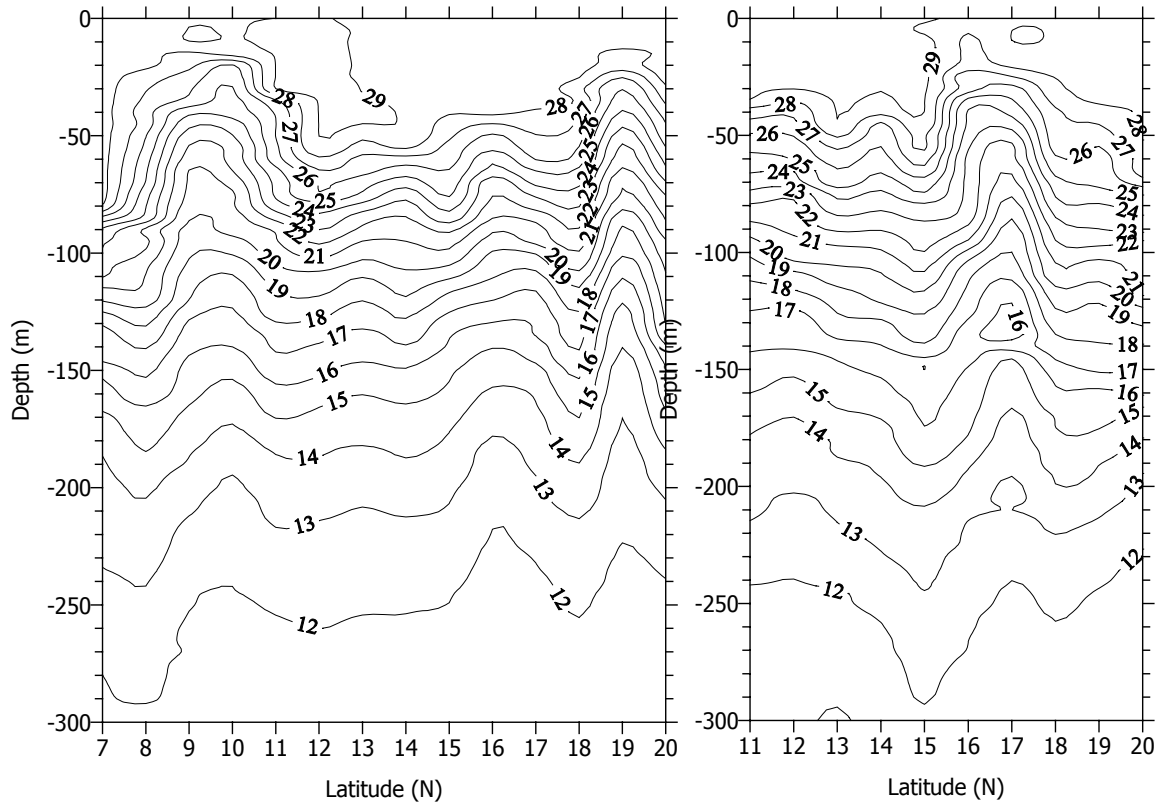


Fig. 2 Vertical structure of temperature in the upper 300m along the open ocean (88°E, left panel) and coastal (right panel) transects.

Salinity structure

The vertical salinity structure along the open ocean transect showed strong gradient in the upper 100m depth. In the surface layer, salinity was about 33.5 psu (practical salinity scale) between 7°N and 15°N but reduced rapidly towards north reaching a low of 27.6 psu at 17°N. The salinity gradient in the upper 50m at 7°N was about 1.5 psu while that at 20°N was about 7 psu, indicating the strong signal of freshwater influx in this region. Below 100m depth, the vertical salinity distribution showed almost homogeneous waters down to 1000m (data not shown) with a salinity of 35 psu (Fig.3 left panel).

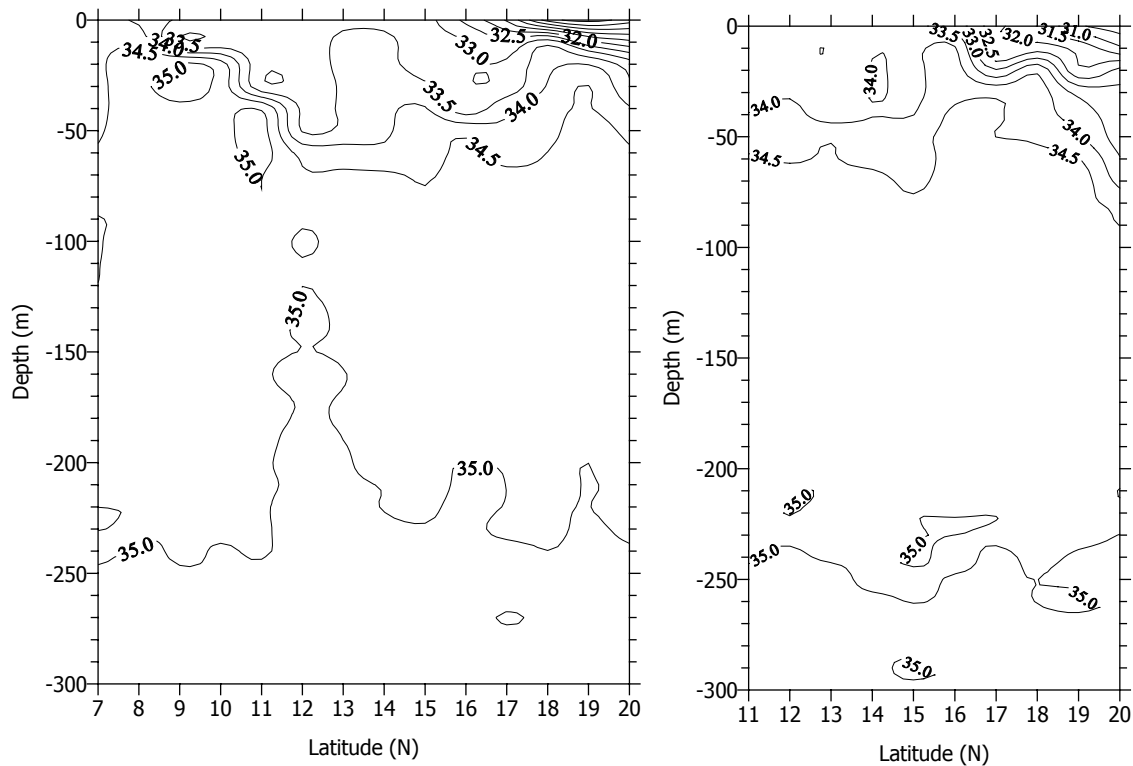


Fig.3 Vertical structure of salinity in the upper 300m along the open ocean (88°E, left panel) and coastal (right panel) transects.

Vertical salinity structure in the upper 300m along the coast also showed strong salinity gradient in the top 100m depth and homogeneous waters with 35 psu salinity below it and up to 1000m. But unlike the open ocean, the salinity gradient south of 15°N was weaker (0.5 psu as compared to 1.5 for the open ocean). In the surface layer the average salinity was 33.7 psu up to 16°N but reduced northward, with the lowest value of 29.6 psu at 19°N (Fig.3 right panel).

Fall Intermonsoon (September-October 2002)

Surface meteorology

Along the open ocean transect (88°E), the wind speed was around 7 m/s from 7°N to 14°N and showed a decreasing trend towards 20°N attaining a value of about 4 m/s (Fig. 4 top left). The surface pressure decreased from 1012 mb at 7°N to 1008 mb at 18°N and then increased to about 1010 mb at 20°N (Fig.4 middle left). The lowest pressure of 1006 mb was associated with the effect of a low pressure area which developed during this time but not very close to the sampling region.

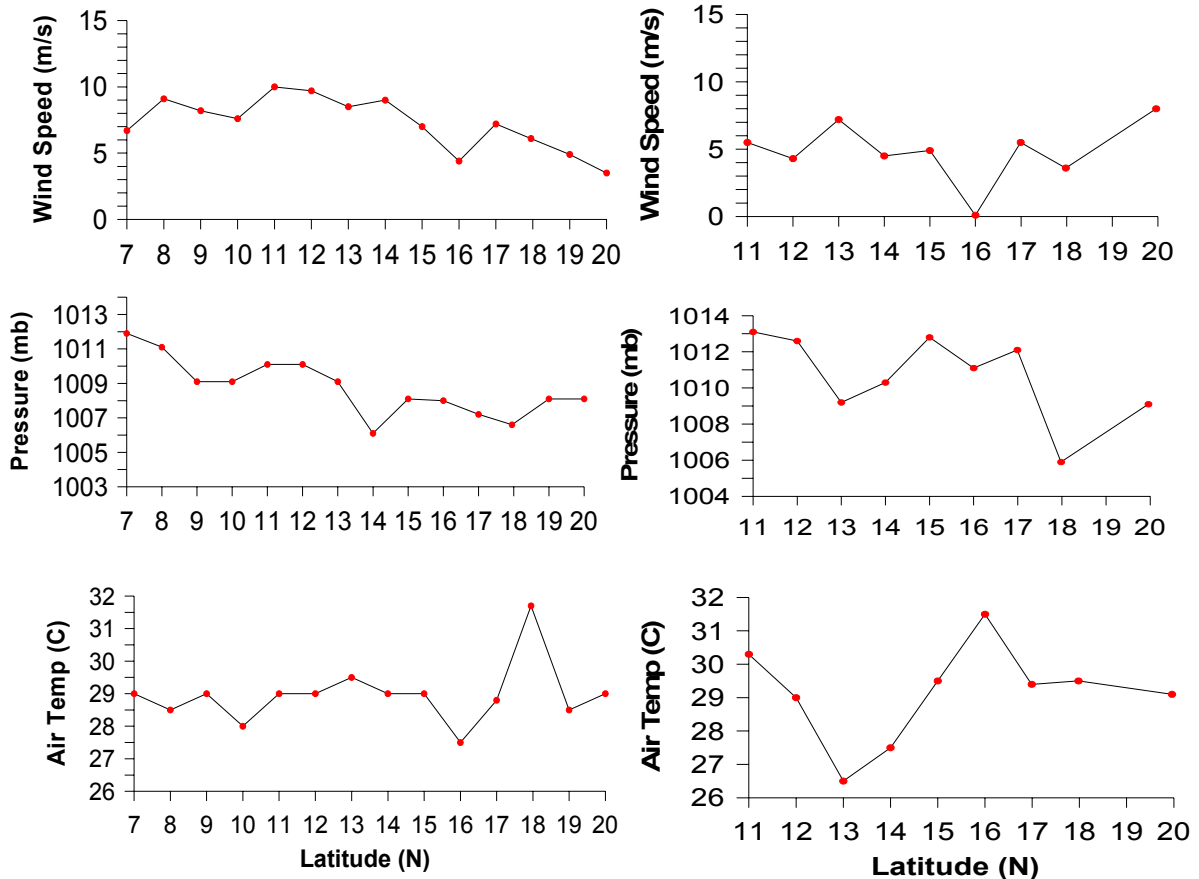


Fig.4 Latitudinal variation of (top) wind speed (middle) atmospheric pressure (bottom) air temperature along open ocean (88°E, left) and coastal (right) transects.

Air temperature on an average fluctuated between 28 and 29°C, with an exception at 18°N where it was in excess of 31°C (Fig. 4 bottom left). Along the coastal transect wind speeds were, low ~ 5 m/s, but unlike along the open ocean transect wind speed increased towards north from 18°N onwards (Fig.4 top right). As in the case of open ocean, the pressure along the coastal transect also showed a slowly decreasing trend superimposed on diurnal cycle up to 17°N and then dropped drastically from 10012 mb to 1006 mb at 18°N (Fig.4 middle right). Air temperature decreased from about 30°C at 11°N to 26.5°C at 13°N and then showed a steady increase up to little more than 30°C at 16°N (Fig.4 bottom right). In general, the atmospheric pressure and air temperature showed much larger variability along the coastal transect than along the open ocean transect (~8 mb and ~5°C respectively).

Thermal structure

The sea surface temperature (SST) along the open ocean transect (88°E) varied marginally from

about 28.2°C to 29°C within 7°N to 17°N, and showed a sharp increase to 29.5°C at 18°N and remained more or less same up to 20°N (SST variations not presented). The mixed layer depth (MLD, defined as the depth at which the sigma-t value exceeds surface sigma-t value by 0.2) was about 25m deep at 7°N, which showed a steady increase towards north, deepening up to 60m at 11°N. North of at 11°N, the MLD decreased steadily shoaling up to less than 5m at 20°N.

Along the coastal transect, SST did not show any definite trend. It was on an average 30°C varying between 29.2°C to 30.5°N. MLD showed a shoaling trend from about 30m in the south to less than 5m towards the north.

The vertical thermal structure along the open ocean transect (88°E) showed the signature of eddies and thermocline oscillation within the upper 300m depth (Fig.5 left panel). Isotherms showed a shoaling from 7°N towards at 9°N and then deepened towards 11°N indicating the existence of cold core eddy. The upper thermocline showed a northward shoaling which was reflected in the mixed layer depth.

Along the coastal transect also the thermal structure showed the presence of oscillations. A cold core eddy signature was inferred with its center at 18°N, where the 27°C isotherm shoaled from 60m to about 15m depth depressing the ambient temperature by about 3°C (Fig.5 right panel).

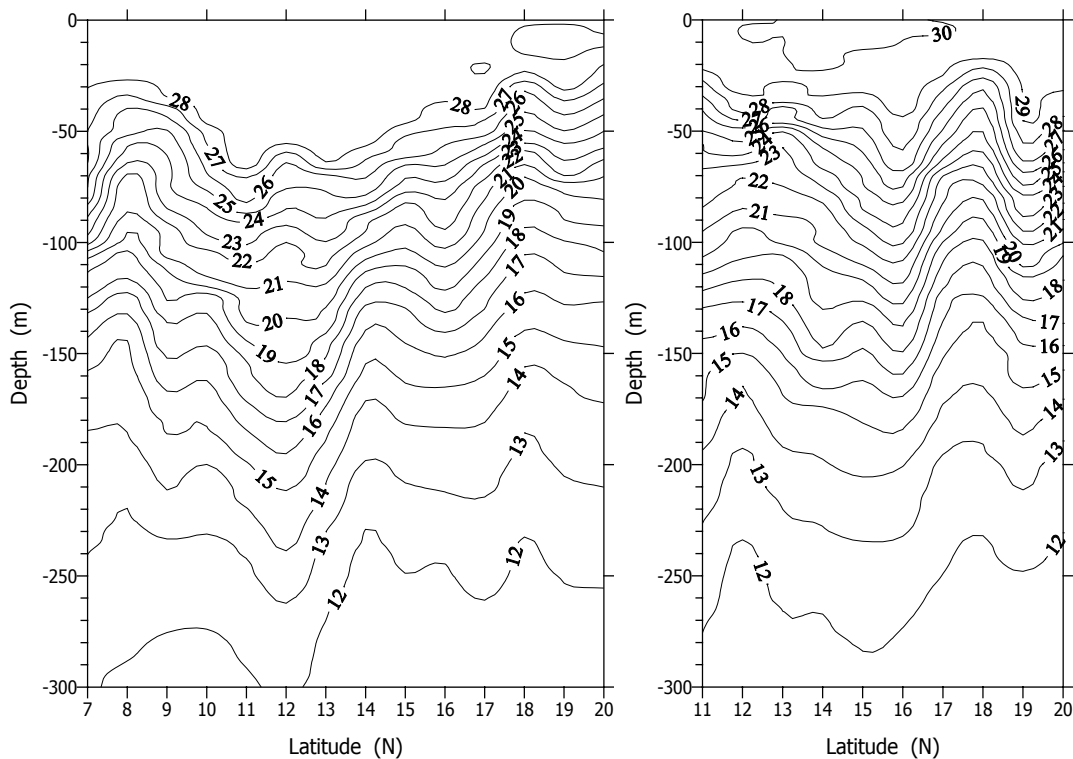


Fig. 5 Vertical structure of temperature in the upper 300m along the open ocean (88°E, left panel) and coastal (right panel) transects.

Salinity structure

Surface salinity along the open ocean transect showed a slow and steady decrease from ~34.0

psu at 7°N to 32.0 psu at 16°N. From 16°N to 17°N the salinity dropped by 3psu and further north, at 20°N salinity was around 28 psu.

Along the coastal transect, surface salinity distribution was similar to that of the open ocean, except that the decrease in salinity from 16°N to 17°N was more (34 psu to 21 psu). Again, the surface salinity in the north was much lower (~23 psu) than that of the open ocean. This trend was similar to the southwest monsoon, which we have already reported.

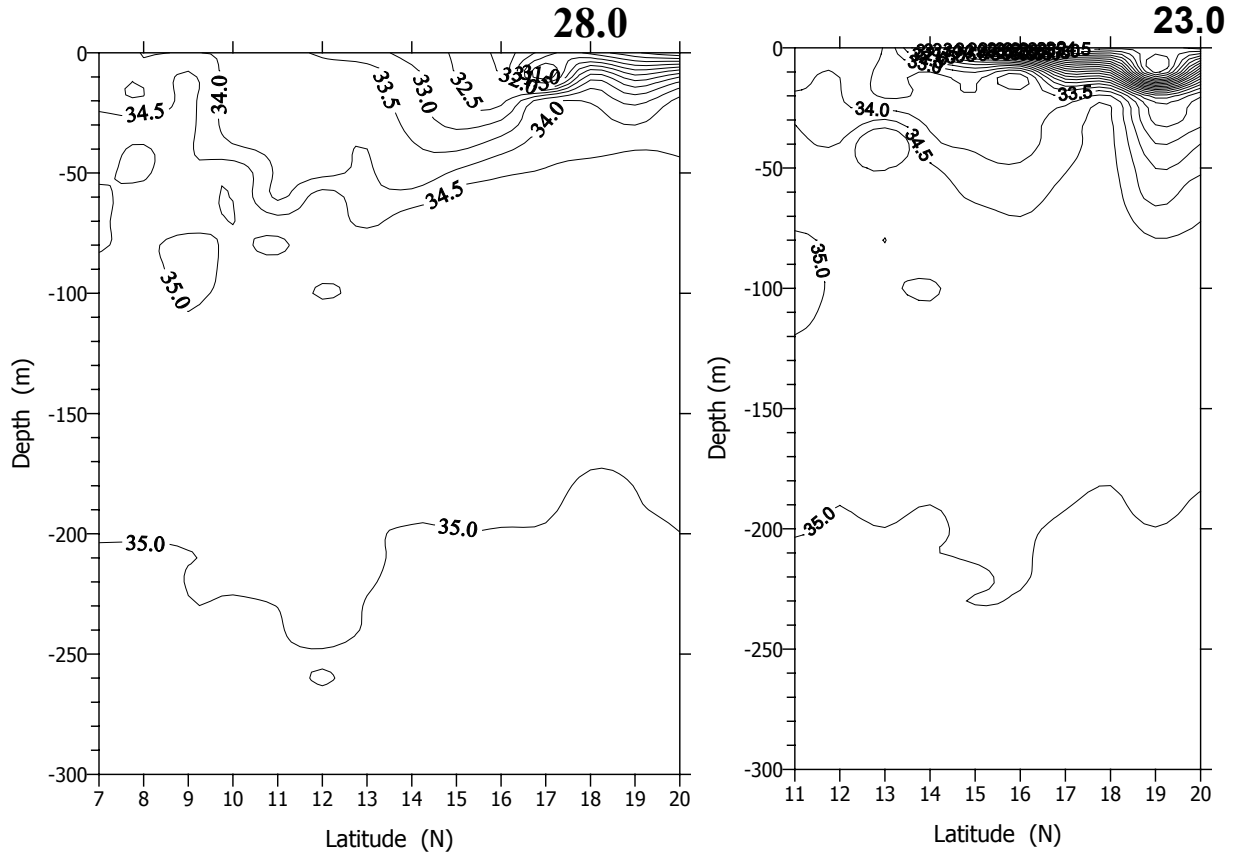


Fig.6 Vertical structure of salinity in the upper 300m along the open ocean (88°E, left panel) and coastal (right panel) transects.

The vertical salinity structure along the open ocean transect showed a strong gradient in the upper 50m, which was more intense towards the north (Fig.6 left panel). The salinity gradient in the upper 50m was about 1 psu in the south (7°N) and increased to 7 psu towards the north. This clearly indicated the influence of the fresh water input, both from river run-off as well as oceanic precipitation, from the north, which moves as a plume over the high salinity ambient water.

Along the coastal transect the salinity structure showed stronger gradients (Fig.6 right panel) both in the south (1.5 psu) as well as in the north (12 psu) in comparison to the open ocean transect.

Spring Intermonsoon (April -May 2003)

Surface meteorology

Along the open ocean transect (88°E), the wind speed was around 7 m/s at 7°N which showed a decreasing trend up to 12°N attaining a value of about 1 m/s and then showed an increasing trend towards 18°N (Fig.7 top left). The surface pressure decreased from 1011 mb at 7°N to 1007 mb at 11°N and then fluctuated between 11°N and 16°N from 1009 to 1012 mb and from 16°N onwards showed a decreasing trend towards north (Fig.7 middle left). Air temperature on an average fluctuated between 29 and 31°C (Fig.7 bottom left).

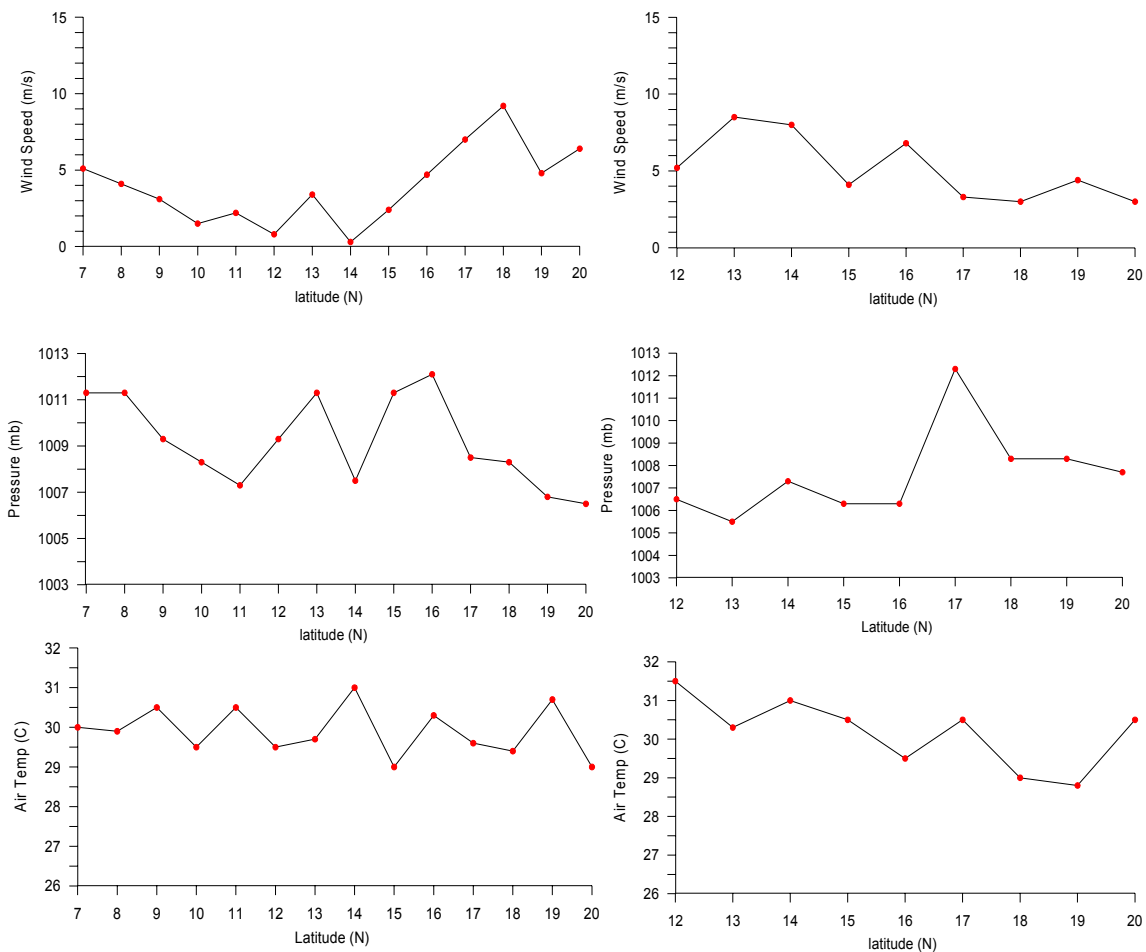


Fig.7 Latitudinal variation of (top) wind speed (middle) atmospheric pressure (bottom) air temperature along open ocean (88°E, left) and coastal (right) transects

Along the coastal transect wind speeds showed decreasing trend from 13°N to 20°N from 8.5m/s to 3m/s (Fig.7 top right). The surface pressure from 12°N to 16°N was on an average 1006 mb. From 16°N to 17°N it showed a sharp increase of 6 mb pressure and from 17°N onwards the

pressure showed a decreasing trend towards 20°N (Fig.7 middle right). The air temperature in general showed a decreasing trend from 12°N to 19°N except at 17°N and 20°N where it showed a slight increase (Fig.7 bottom right).

Thermal structure

The sea surface temperature (SST) along the open ocean transect (88°E) varied between 31.5°C to 29.5°C (SST variations not presented). The mixed layer depth (MLD, defined as the depth at which the sigma-t value exceeds surface sigma-t value by 0.2) was about 33m deep at 7°N, which further deepened to 42m deep at 8°N. From 8°N onwards MLD variation showed a shoaling trend and it shoaled as low as 3m at 11°N and then on showed a deepening trend up to 17°N and once again showed a decreasing trend towards 20°N.

Along the coastal transect, SST varied between 30.5°C to 29°C from south to north in general showing a decreasing trend from south to north. MLD showed a shoaling trend from 36m in south to 25m towards the north.

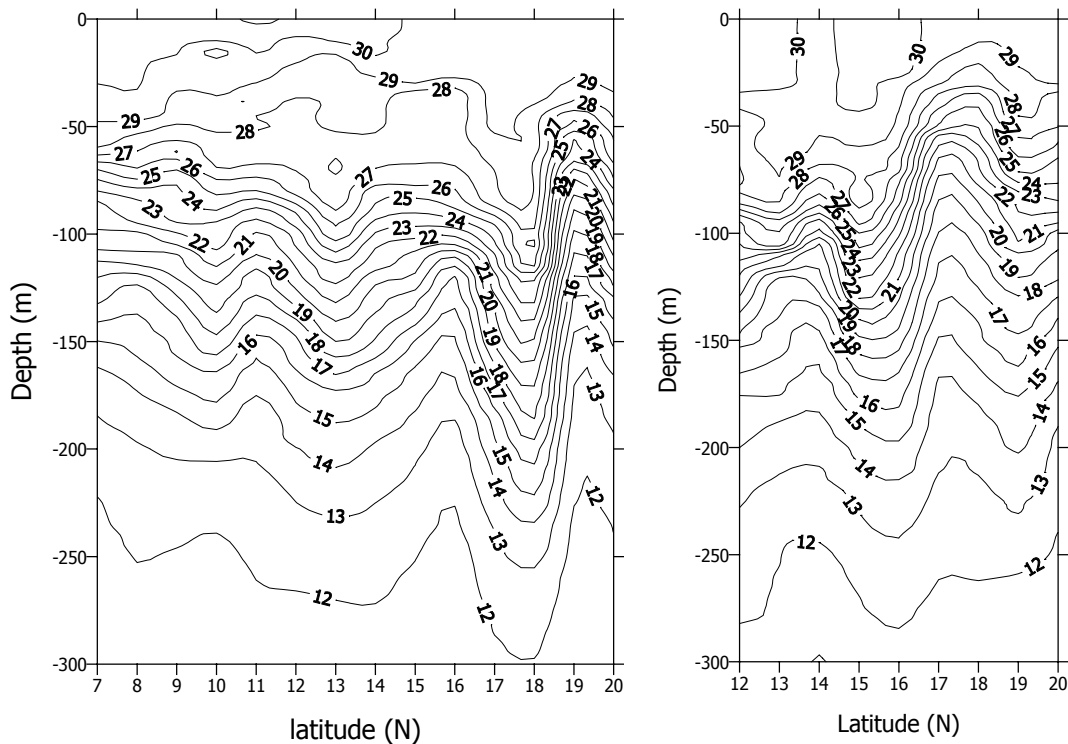


Fig.8 Vertical structure of temperature in the upper 300m along the open ocean (88°E, left panel) and coastal (right panel) transects.

The vertical thermal structure along the open ocean section during spring Intermonsoon showed a thin isothermal layer of about 10m in the south, south of 15°N, within which the temperature was in excess of 30°C (Fig.8 left panel). Towards the north, the isothermal layer was thicker (~30m) and 1°C colder. In general, the isotherms in the upper 50m showed a shoaling trend from 7°N to 15°N, while further north it deepened towards 17°N and once again shoaled at 19°N. However, below 50m there was a reversal in the slope of isotherm, which showed a deepening

trend from 7°N towards 18°N. At 11°N, the up/down sloping of isotherm was the least, while that at 19°N was the maximum. For example, the 22°C isotherm shoaled by 20m at 11°N and 16°N depressing the ambient temperature at 120m by 2-3°C. At 19°N the shoaling exhibited by 22°C isotherm was as large as 70m, which resulted in a drop in the ambient temperature at 120m by about 7°C. The up/down sloping of isotherm centered at 16°N was seen even in deeper depths right up to 1000m.

Along the coastal transect thermal structure showed comparatively deep isothermal layer south of 16°N with a thickness of about 40m and temperature in excess of 30°C (Fig.8 right panel). Towards the north the isothermal layer was thin, about 10m, and the temperature of this layer was about 1°C colder. In general, the isotherm in upper thermocline showed a northward shoaling with 29°C isotherm located at about 70m deep in the south, which shoaled to about 10m in the north. The most prominent feature was the up/down sloping of isotherm centered at 14°N and 17.5°N, the latter being the most pronounced one. Interestingly the amplitude of isotherm displacement, though seen towards the deeper layers in both the cases, was greater for the former. For example, at 14°N, the 22°C isotherm shoaled by about 30m, while that at 17.5°N was about 70m. On the contrary, in the deeper layers, the 10°C isotherm showed a shoaling of about 140m where as it shoaled only by 40m at 17.5°N. Thus, the vertical displacement of isotherms at 100m resulted in depressing the ambient temperature by about 3°C and 5°C at 14°N and 17.5°N respectively.

Salinity structure

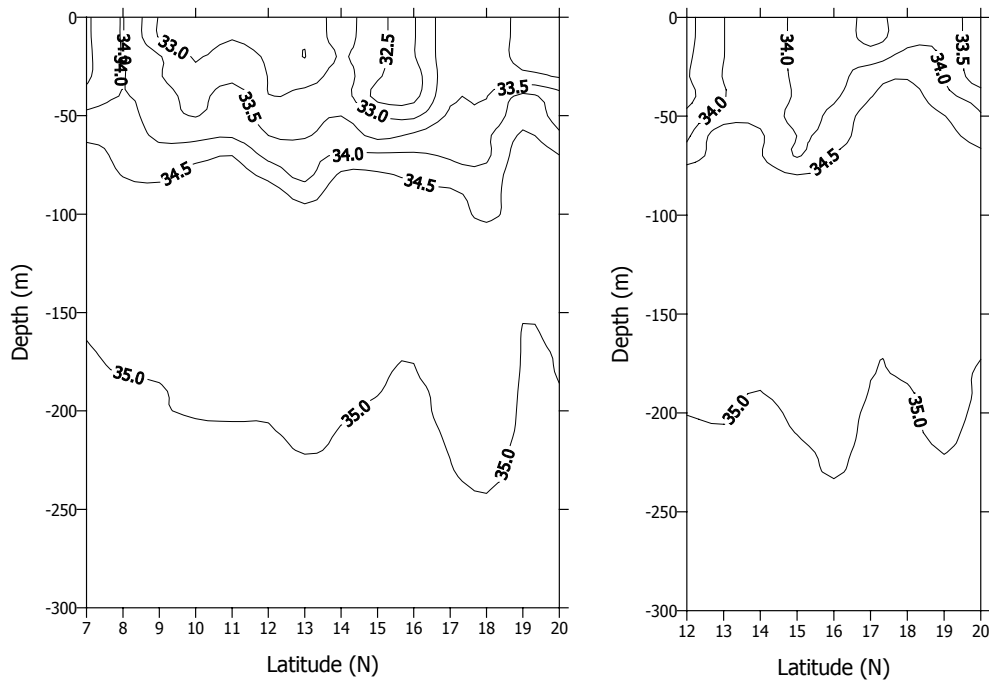


Fig.9 Vertical structure of salinity in the upper 300m along the open ocean (88°E, left panel) and coastal (right panel) transects.

Surface salinity along the open ocean transect varied between 32.5 to 34psu. The vertical salinity structure along the open ocean showed an isohaline layer of about 30m thickness having a salinity of about 33psu, except between 16° and 17°N, and south of 9°N (Fig.9 left panel). In the former, salinity was 0.5psu fresher while in the latter salinity showed a steady increase. The

halocline was located between 30 and 100m depth, within which the salinity increased by 1.5psu north of 9°N. In the south, however, the gradient in the vertical salinity showed steady decrease. Salinity distribution showed only marginal variation between 100m and 1000m. Interestingly, isohalines in the upper 100m showed up/down sloping centered at 11°N, 16°N and 19°N.

The vertical salinity structure along coastal transect also showed a gradual shoaling of isohalines from south towards north with 0.5psu fresher waters in the north compared to south (Fig.9 right panel). Accordingly, the vertical gradient of salinity in the upper 100m was only 1psu in the north and 0.5psu in the south. Consistent with thermal structure, salinity distribution also showed prominent isohaline displacements centered at 14°N and 17.5°N. However, unlike that of the thermal structure, the oscillation in the isohaline centered at 17.5°N was not evident in deeper layers.

Winter monsoon (November 2005- January 2006)

Surface meteorology

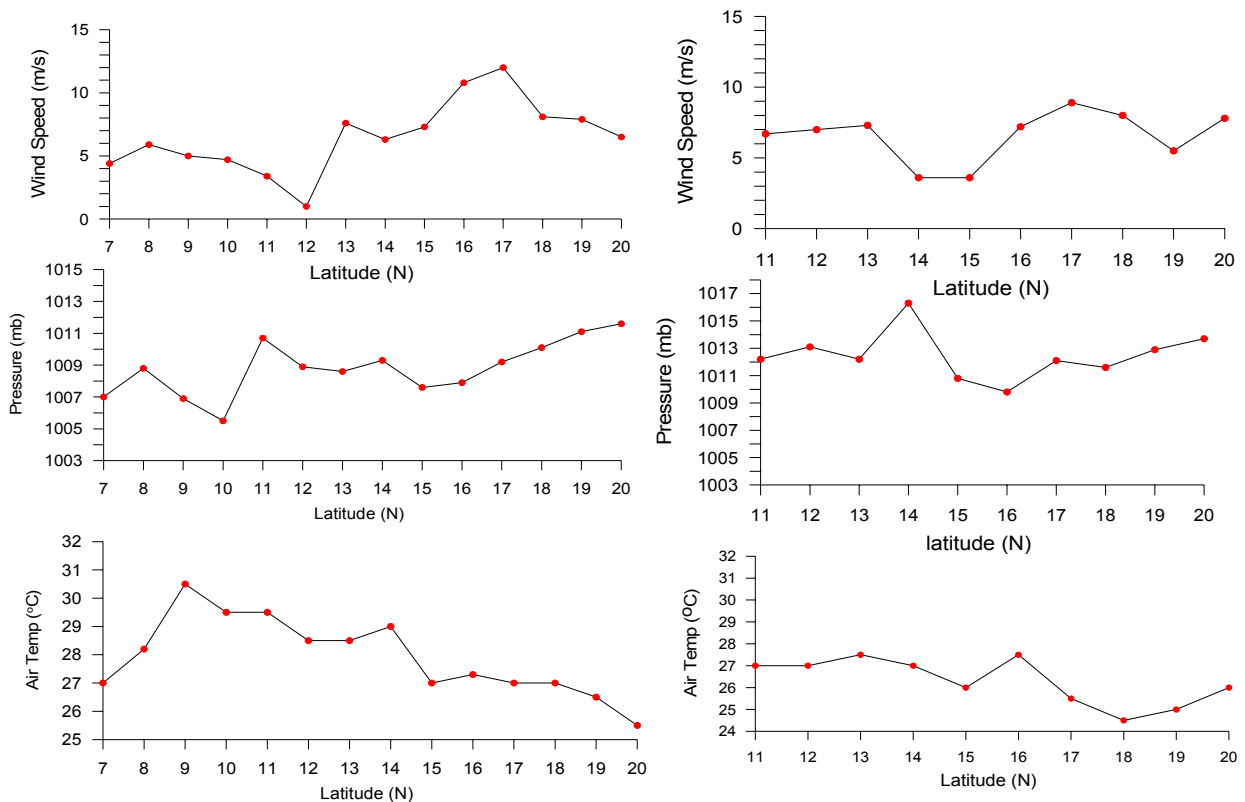


Fig.10 Latitudinal variation of (top) wind speed (middle) atmospheric pressure (bottom) air temperature along open ocean (88°E, left) and coastal (right) transects.

Along the open ocean transect wind speed was 6 m/s at 8°N which decreased to 1 m/s at 12°N and then showed an increasing trend reaching a value of 13m/s at 17°N then showing a gradual decrease towards 20°N (Fig.10 top left). Surface pressure was 1007 mb at 7°N which increased by 2 mb at 8°N. From 8°N the pressure was 1009 mb, which then decreased to 1005 mb at 10°N, pressure then started increasing gradually towards north (Fig.10 middle left). Air temperature

along the open ocean showed a sharp increase from 7°N to 9°N with increase from 27°C to 30.5°C and then onwards showed a gradual decrease up to 20°N (Fig.10 bottom left)

Wind speed along the coastal transect fluctuated between 4 to 9 m/s (Fig.10 top right). Along the coastal transect air pressure showed an increase of 4 mb from 11°N to 14°N. From 14°N to 16°N the pressure decreased by 7 mb and then onwards showed a gradual increase towards 20°N (Fig.10 middle right). Air temperature in general showed a decreasing trend, except at 16°N where it showed an increase of 1.5°C (Fig.10 bottom right)

Thermal structure

The vertical thermal structure along the open ocean transect (88°E) showed the signature of eddies and thermocline oscillation within the upper 300m depth (Fig.11 left panel). Isotherms showed a shoaling from 8°N towards at 10°N and then deepened towards 13°N indicating the existence of cold core eddy. The upper thermocline showed a northward deepening which was reflected in the mixed layer depth.

Along the coastal transect also the thermal structure showed the presence of oscillations. A cold core eddy signature was inferred with its center at 12°N, (Fig.11 right panel). Another cold core eddy was inferred with its center at 14°N. Isotherms showed a deepening from 16°N to 20°N

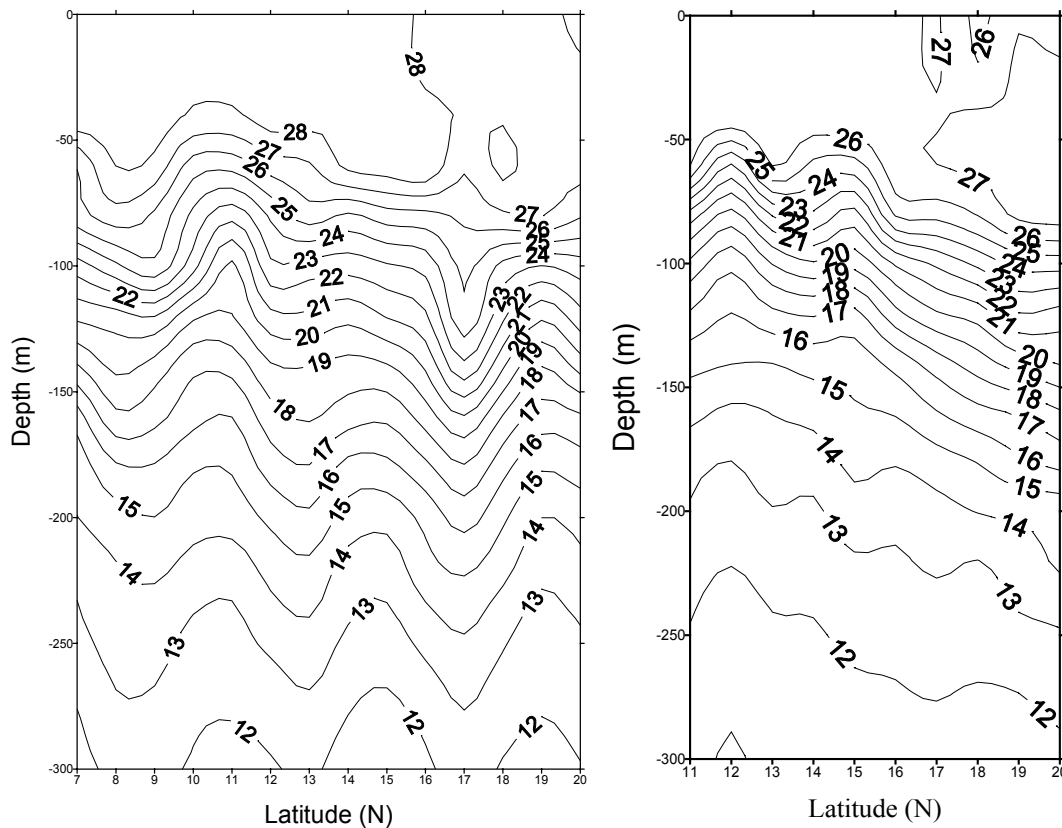


Fig.11 Vertical structure of temperature in the upper 300m along the open ocean (88°E, left panel) and coastal (right panel) transects.

Salinity structure

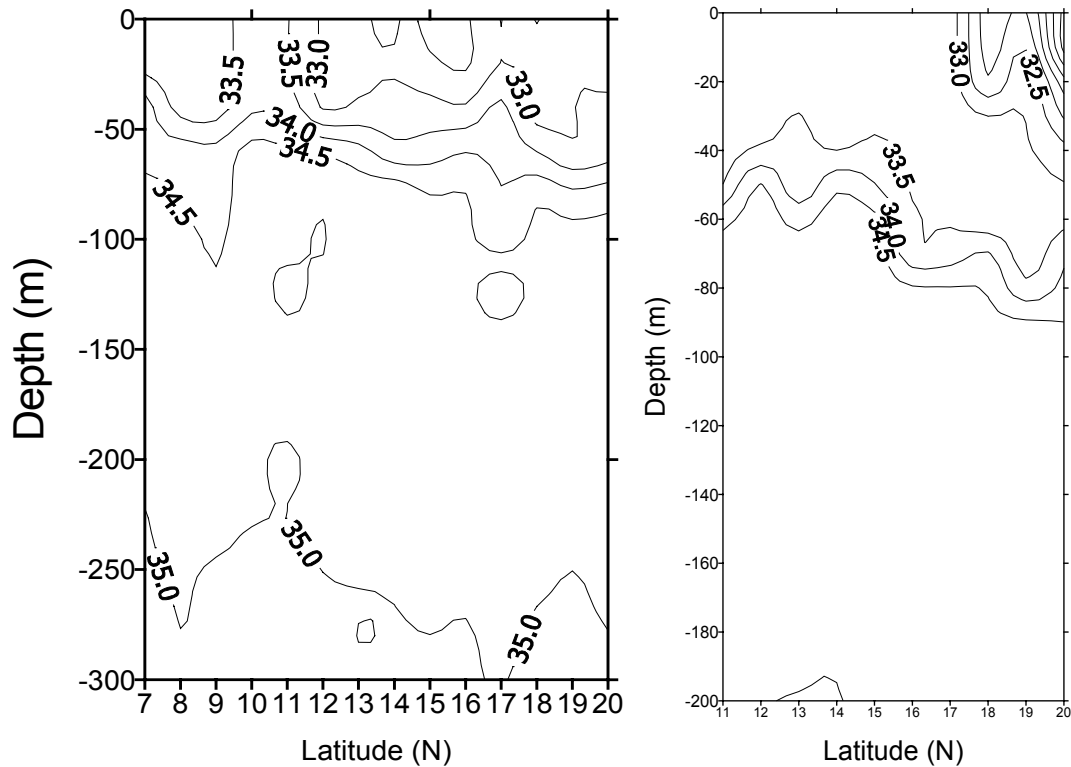


Fig.12 Vertical structure of salinity in the upper 300m along the open ocean (88°E, left panel) and coastal (right panel) transects.

The vertical salinity structure along the open ocean showed an isohaline layer of about 30m thickness having a salinity of about 33.5psu, except between 9° and 11°N (Fig.12 left panel). Salinity showed a decrease of 0.5psu from 12°N to 20°N. The halocline was located between 40 and 100m depth, within which the salinity increased by 1.5 psu north of 11°N. In the south, however, the gradient in the vertical salinity showed steady decrease. Salinity distribution showed only marginal variation below 100m.

The vertical salinity structure in the upper 300m along the coast showed a isohaline layer from 11°N to 17°N with salinity of 34psu and also showed strong salinity gradient north of 17°N in the top 50m depth with salinity gradient of 3psu. (Fig.12, right panel).

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4. Biological Programme

4.1 Biological productivity characteristics in the Bay of Bengal

Participants:

National Institute of Oceanography, Goa

Dr M Mahupratap	Principal Investigator (till 7th January, 2004)
Dr N Ramaiah	Principal Investigator (from 8th January, 2004)
Dr Mangesh Gauns	
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Ms Asha Nadurmath	
Ms Sapana Nabar	

Objectives

- (1) To study the primary production rates; understand its temporal and spatial variations and role in carbon fluxes.
- (2) To compare ground truth chlorophyll values with satellite imageries
- (3) To relate the influence of primarily fixed carbon on the secondary production
- (4) To study the standing stocks of micro - and mesozooplankton with a view to gain an insight into the quantities of carbon in this biomass and regenerated production
- (4) To understand the seasonal shifts in the generic/species composition of micro - and mesozooplankton
- (5) To study the bacterial abundance, production rates and ATP concentrations.

Introduction

The Arabian Sea (AS) and the Bay of Bengal (BoB) form excellent natural crucibles for studying the variability in the biogeochemistry of the oceans. Both being enclosed in the north at similar latitudes, the AS on the west and the BoB on the east are bordering the Indian subcontinent. These relatively small tropical basins come under the influence of the seasonally reversing monsoons. There are, however, many differences - the latter is partially connected to the Pacific through the Australasian sea-ways contributing to both physical and biological exchanges. Differences between the physical and chemical regimes of AS and BoB arise mainly through opposing trends in surface circulation during summer (South-West) and winter (North-East) monsoons and, the quantum of discharge of fresh water (about 195×10^6 tons y^{-1} in the AS compared to an imposing $\sim 1387 \times 10^6$ tons y^{-1} ; Subramanian, 1993) and associated suspended sediment discharge (1.5 billion tons into the Bay *versus* a mere 100 million tons into the AS).

Under Joint Global Ocean Flux Studies (JGOFS), the AS was one of the prime area for investigations along with the Atlantic, Pacific and Southern Ocean. With the successful completion of JGOFS (India) Programme in the recent past, we have acquired considerable data sets from the AS. On the other hand, information on the BoB has only been scanty. For this reason, as a follow up of JGOFS in AS, the Bay of Bengal Process Study (BOBPS) was planned and executed with an aim to cover seasonal and interannual changes and understand the processes that drive the biogeochemistry of the region.

The BOBPS aimed to test the following hypotheses (1) The riverine inputs influence the BoB physical features and thus, biological production and, (2) these altered features ultimately influence the carbon fixation, CO_2 fluxes and carbon sequestered into the deep. With these aims, we undertook the first BOB Process Study in July-August 2001 covering two transects, one along the open sea ($88^\circ E$) and another along the eastern coast of India (within $81 - 85^\circ E$). It may

noted that the coastal track was along a deeper track (depth often exceeding 1500m) because of the narrow shelf.

Parameters measured

Chlorophyll *a*
Primary Production
Phytoplankton Types
Bacterial Abundance
Bacterial Production Rates
Microzooplankton
Mesozooplankton
Particulate Organic Carbon

These measurements were made during four cruises from nine pre-decided stations representing the open ocean and western margin ecosystems of the Bay.

Methods

Sampling

Sampling was done onboard ORV Sagar Kanya during the first three cruises (July-August 2001 [summer monsoon], Sept-Oct 2002 [fall intermonsoon], April-May 2003 [spring intermonsoon] and the last one onboard FORV Sagar Sampada (Nov 2005- Jan 2006 [winter]. The cruise track and station positions are shown EARLIER. All samples for biological studies were collected and processed as per JGOFS Protocols (UNESCO, 1994). Water samples were drawn from different depths using a CTD (Sea Bird Electronics) rosette sampler fitted with 12 litre capacity Go-Flo bottles for estimating standing stock of microzooplankton, phytoplankton, and bacteria. ^{14}C and ^3H -Thymidine techniques measured phytoplankton and bacterial production rates, respectively. Mesozooplankton samples were collected with a Multiple Plankton Net (MPN, Hydrobios, mouth area 0.25m^2 , mesh size 200 micron) from upper 120m water column. Analyses of these parameters are detailed below:

*Phytoplankton biomass (Chlorophyll *a*)*

One litre of water sample from the depths (0, 10, 20, 40, 60, 80, 100 and 120m) were filtered through 47mm GF/F filter paper ($0.7\mu\text{m}$ pore size). Chlorophyll *a* (Chl *a*) was extracted in 10 ml 90% acetone in the dark for 24 hrs in a refrigerator. A fluorometer (Turner Designs, USA) was used for measuring fluorescence and the observed chl *a* (mg m^{-3}) values were converted to carbon using 50 as a conversion factor (Banse, 1988).

Primary productivity (PP)

Water samples from depths mentioned above were collected predawn and transferred to 300ml capacity polycarbonate (Nalgene) bottles. These bottles (3 light, 1 dark) were then incubated *in-situ* at the respective depths from half an hour before sunrise to half an hour after sun set (~ 12hrs local time) after adding 1 ampoule of ^{14}C (185 kBq) to each bottle. The initial and final adsorption of the ^{14}C by particles was measured after filtering 100ml of sample from each bottle onto a 25mm diameter GF/F filter paper ($0.7\mu\text{m}$). Sample filters were fumed overnight with 0.5

N HCl and analyzed for radioactivity in a Packard 2500TR counter after adding 5ml of liquid scintillation cocktail.

Calculations

Production ($\text{mg Cm}^{-3} \text{d}^{-1}$) = $((S_{\text{DPM}}/V) \times (W \times 10^{-3}) / T_{\text{DPM}}) * (1.05/T)$

Where: S_{DPM} = Disintegration per minute in filtered samples; V = Volume of filtered water (liters); W = DIC concentration in samples (approx $25000 \text{ mg C m}^{-3}$, should be measured for non-oceanic habitats); T_{DPM} = Total ^{14}C DPMs (in 0.25 ml); 0.25×10^{-3} = Conversion of pipette volume to litres; 1.05 = Correction for the lower uptake of ^{14}C compared to ^{12}C and T = Time (days).

Phytoplankton cell counts (>5 μm)

Subsamples of 250ml from all the eight depths as above were fixed in 1% Lugol's iodine and preserved in 3% formaldehyde solution. All the samples were left in the dark at low temperature until further analysis carried out in the laboratory. A settling and siphoning procedure was followed to concentrate samples. Subsamples of these concentrated samples were then examined microscopically (1ml in triplicate) in a Sedgwick-Rafter plankton counting chamber at 100X magnification.

Bacterial abundance

Aliquots of 100ml obtained from different depths as above were fixed with 3.7% of 0.22 μm -filtered formaldehyde and stored at 4°C until taken up for counting total bacterial cells. At many locations, samples up to 1000m were collected for assessing bacterial abundance. Microscopic slides were prepared as per the JGOFS protocols (UNESCO, 1994) and acridine orange direct counts (AODC) made under oil immersion objective on Olympus BH2 epifluorescence microscope. Cell numbers were converted to carbon using a factor of 11 fg C per cell (Garrison et al., 2000).

Bacterial production (BP)

Water samples (20ml in triplicate) from each of the 8 depths in the top 120 m column mentioned above [and, from deep from some selected locations] for bacterial abundance were incubated for 1hr after adding tritiated ^3H -methyl thymidine to a final concentration of 10nM. The aliquots were filtered on to 0.2 μm Millipore filters and, rinsed with ice-cold trichloroacetic acid and ethanol to extract and bind the DNA to the membranes. All filters were stored in dark until taken up for radio-activity assays in the lab. They were assayed in a Packard 2500TR counter, after adding 5 ml of liquid scintillation cocktail.

Calculations

Bacterial production ($\text{pMh}^{-1}\text{I}^{-1}$) = $(\text{DPM}_s - \text{DPM}_b) / 2200 \times V / 1000 \times 60 / T \times 1 / \text{SA}$

Where, DPM = Disintegration per minute in filtered samples (s) and blank (b); V = Sample volume (ml); T = Incubation time (minutes) and SA = Specific activity of ^3H -thymidine.

Microzooplankton (Mzp)

From each depth (0, 20, 40, 50, 80, 100, 120 and 150m), ten litres of 200µm screened water sample was gently siphoned through a PVC tubing with its cod end fitted with a 20µm Nitex screen. All samples were concentrated to ~ 100ml and preserved in 1% acid Lugol's solution (final concentration). Identification, counting and sizing of microzooplankton were carried out following standard and established methods in literature. An inverted microscope with phase contrast optics at 100-400X magnification was used for these analyses. The length and breadth from 50 individuals of each group (ciliates, heterotrophic dinoflagellates, sarcodines and micrometazoans) were measured using ocular micrometer and converted to biovolume using appropriate geometric formulae. Carbon was estimated from biovolumes by using different biovolume to carbon conversion factors for ciliates, heterotrophic dinoflagellates, sarcodines and naupliar stages.

Mesozooplankton biomass (ZP)

Samples collected by vertical hauls from five depths in the 0-1000m column using multiple plankton closing net (200µm, Hydro-Bios) were used for biomass estimation by displacement method. The biomass was converted to dry weight using a factor of 0.075 g dry wt. per ml of displacement volume and then to carbon as 34% of the dry weight.

Total living carbon (TLC) was calculated as the sum total of chlorophyll *a*, bacteria, microzooplankton and mesozooplankton standing stock.

Results

For any oceanic/marine region to be biologically stable, diverse and productive, the microalgal photosynthetic activity is of paramount importance. A reliable measure of microalgal abundance is through the determination of chlorophyll (chl). Higher the chlorophyll concentration, higher would be the possible biological activity. While there were a few higher concentrations of chl *a* at some locations, there was no drastic difference in its distribution in the BoB during different seasons. The 0-120 m column integrated chl *a* did not show significant seasonal differences although its subsurface maxima deepened up to 80m during the spring intermonsoon. The seasonal differences of 0-120 m column integrated chlorophyll *a* at different sampling locations are depicted in Fig 1 a-d. A comparative account of chlorophyll *a* carbon (mg Cm^{-2}) in the 0-120 m column in the open ocean and along the coastal stations of Arabian Sea and Bay of Bengal during different seasons (Table 1) suggests that the chl *a* biomass in the AS is greater than that in the BoB. While many detailed analyses of phytoplankton composition in the BoB are on, the major and very preponderant genera/species are listed in Tables 3a and 3b.

While the influence of nitrate and silicate concentrations on the primary production (PP) was implicit, cold-core eddies at 9 °N 88 °E and 17 °N 85 °E enhanced chlorophyll and primary production apparently suggesting their strong influence on biological productivity. Our observations suggest that the primary production in the Bay is somewhat higher during the fall intermonsoon followed by summer monsoon and spring intermonsoon (Table 1). PP results from winter 2005 are yet to be obtained. A comparative account of PP ($\text{mg Cm}^{-2} \text{d}^{-1}$) in the 0-120 m column in the open ocean and along the coastal stations of Arabian Sea and Bay of Bengal during different seasons is available in Table 2. In fact, PP values ranging from 3.0 to 8.7 $\text{g C m}^{-2} \text{d}^{-1}$ have been reported from inshore waters during June-July. Further, the post-1980 investigations during August-September 1978 concluded that "the PP of BOB is not less than

that reported from the AS". From our studies, however, it can be suggested that the PP (see Fig 2) in the Bay remains lower compared to the AS. Further, most other studies too record less than $0.5 \text{ g m}^{-2} \text{ d}^{-1}$ or lower along with very low chlorophyll *a* (chl *a* 9 to 19 mg m^{-2}). Thus, rapidly diminishing euphotic depth (from about 40-50m in open ocean to $< 6 \text{ m}$ inshore) along with lack of major upwelling regions (unlike the AS) may be the plausible reasons for the low primary production in the BoB. Lower primary production as a consequence of unfavorable physical, atmospheric and turbidity regimens would also lead to correspondingly low BP and secondary production.

Ubiquitous and abundant heterotrophic bacteria are key players in ocean biology and, are important components of marine biomass. They form food for protozoa, invertebrate larvae and many large zooplankton. Further, they regenerate dissolved nutrients required for marine photosynthesis and formation of newer organic biomass. In addition, they are pivotal in remineralizing the dead organic matter releasing many inorganic dissolved nutrients such as NO_3 , PO_4 , SiO_3 , CO_2 , H_2S etc which govern the marine chemosynthesis and fuel the biogeochemistry of the oceans. In general, Bacterial biomass in the BoB are higher than those reported from the Arabian Sea. Seasonal differences in bacterial numbers and production rates at different sampling locations are depicted in Fig 3. Abundance of bacterioplankton in the BoB are generally comparable to ranges reported from different regions of tropical oceanic waters. Although the observed bacterial production (BP) rates are lower than those in the productive Arabian Sea, it is quite intriguing that the bacterial abundances are higher. In the Bay, bacterioplankton [quite abundant with $10 \times 10^8 \text{ cells l}^{-1}$ in the CB and $19 \times 10^8 \text{ cells l}^{-1}$ in the WB] attained maximum numbers usually at the upper boundary of the thermocline where higher biomasses of mesozooplankton were recorded.

The water column microfauna in the size range of 20-200 μm , the microzooplankton, can be called operators of microbial loop in the marine environment. All protozoa, invertebrate larvae, early stages of mesozooplankton $< 200 \mu\text{m}$ fall in this category. They also form food of many mesozooplankters and fish larvae. Together with heterotrophic bacteria, microzooplankton are pivotal in extending and sustaining deep-sea fauna. Microzooplankton biomass was low and did not indicate drastic spatial variations. But there were temporal variations (Fig 4). Tintinnid ciliates and heterotrophic dinoflagellates were the predominant fauna.

Mesozooplankton biomass (Fig 5a-d) and predominant groups observed during the 2002 post-monsoon months of September and October are listed in Table 4. Strong seasonal shifts in mesozooplankton composition were also evidenced. Detailed analyses of the samples will be done to understand the community structure as well as ecological processes bringing about biological variability.

The BoB is traditionally considered having poorer biological productivity compared to its western counterpart, the AS. Although the riverine flux is expected to bring-in large amount of nutrients, they are thought to be lost either within the river mouths or, to the deep because of its narrow shelf. Comparatively heavier cloud cover may be another reason. As it is a cyclone-prone area, such episodic events are likely to churn-up the area injecting nutrients to the shallow euphotic zone (due to turbidity arising from sediment influx) enhancing production at least for a short while.

The living carbon biomass in the 0-120 column varied with seasons (Table 5). Heterotrophic bacteria are prominent contributors to this biomass almost throughout the year. The average bacterial biomass equaled 29 % of phytoplankton biomass in the CB and as high as 91% in the

WB. Though puzzlingly slower in growth rates, this high biomass in the WB implies that the heterotrophic bacteria are efficient in assimilating the allochthonous organics and, are far more important in the food web dynamics of the coastal BoB.

In general, the Chl *a*, PP, BP, TOC and microzooplankton numbers were more in the south of 15°N along 88°E. In the Western Bay (WB), Chl *a*, bacterial carbon, PP and TOC showed increases northwards during most seasons. As the microzooplankton abundances have been more in the southern region of the BoB, it is quite likely that the heterotrophic bacteria respond to grazing pressures and have a relatively rapid turnover. This can be indirectly evidenced from the high bacterial biomass as well as faster BP south of 15°N. Aloricate ciliates and heterotrophic flagellates were discerned as the predominant groups that are main bacterivores among the microzooplankton. Grazing by these groups on bacteria appears to be an important event in the trophodynamics of the BoB. Thus, heterotrophic pathway of energy transfer apparently is more prominent in the low chlorophyll productivity regions of the Bay. As bacteria are primarily responsible for assimilating the dissolved organic matter even in the deep sea and their role as forage and in deep-sea faunal biomass production, it is important to understand their relationship with other microheterotrophs. Keeping this in mind, the data collected under BOBPS on bacteria, micro- and meso- zooplankton will be further analyzed for an understanding of trophodynamics and carbon biomass distribution in the BoB.

Assuming that a substantial proportion (>90%) of TOC is DOC, the observed TOC levels in the WB do suggest the availability of over 1000 mg m⁻³ (>80 μM) of DOC in the water column below 120 m. This is in addition to the DOC that is exported from daily photosynthesis, phytoplankton exudates and from cellular materials released from sloppy feeding of zooplankton [including those vertically migrating and aiding the rapid downward transport of TOC], viral lysis, faunal excreta, carcass fragmentation and decomposition, and natural mortality of phytoplankton. Further, a number of subsurface maxima in bacterial abundance were also observed and the abundances increased with depth in the WB. This could be possibly due to the higher amounts of carbon fluxes in to deeper regions in the coasts. From such abundances and their subsurface maxima, it can be suggested that higher bacterial abundances in the deep BoB are unique. Increased flux of organic carbon to the subsurface in the northern latitudes due to ballast effect from the river derived mineral particles settling onto organic aggregates may accelerate particle sedimentation in the water column and in turn help heterotrophic bacterial abundance. Thus, bacteria and the heterotrophic food chain appear important in sustaining microzooplankton as well as mesozooplankton through the microbial loop (?).

Supply of energy and carbon from preponderant diatoms and, microheterotrophic communities are apparently of greater significance for zooplankton in the Bay. A combination of bacteria and other microheterotrophs being 'more complete and highly nutritious' and ingesting them even indirectly via aggregates or, directly by some tunicates and the like, would be a more efficient means for zooplankton and macrofaunal growth and sustenance. Mostly never considered in the classical food webs, these small sized organisms with very high carbon standing stocks may be playing a major role. The larval stages are certainly benefiting by ingesting aggregates fortified with microheterotrophs. In addition to remineralizing most of the inorganic nutrients essential for autotrophic production in the euphotic zone of the Bay, the capacity of microheterotrophs, heterotrophic bacteria in particular, in assimilating DOM and POM in the deep is certainly far more important than we have so far realized.

While surface stratification and higher suspended loads are greater hindrances to the general productivity and overall biology of the Bay, persistent cold core eddies in the central Bay around

9 °N and in the northwestern Bay are apparently important in enhancing the biological productivity at least in some pockets. Thus, more understanding and elucidation through further studies on important physical features of the Bay seem to hold answers to the possible low productivity there.

In conclusion, the salient points that emerge from this work are as follows:

- Chlorophyll remains subsurface throughout the year; deepest in NEM
- PP severely limited by freshwater capping and poor pumping-up of nutrients
- Shallow euphotic depths ($\sim < 55\text{m}$) not conducive for higher Column PP
- Bacteria abound- far more than those in the AS; appear very crucial for microheterotrophs in southern and, open-ocean regions of the Bay
- Microzooplankton much poorer than those in the AS except for SpIM
- Mesozooplankton biomass mostly decoupled with chl *a* and PP
- Cold-core Eddies do bear an enhancing influence on the overall biological processes

Table 1. Comparative accounts of chlorophyll *a* (mg Cm⁻²) in the 0-120 m column in the open ocean and along the coastal stations of Arabian Sea and Bay of Bengal during different seasons. Arabian Sea Data from JGOFS (India) Programme.

Seasons	Arabian Sea			Bay of Bengal			
	SpIM	SuM	Win	SpIM	SuM	FIM	Win
Locations							
				<u>Open Ocean</u>			
11° N64°E	360.25	2193.75	653.50	9°N 88°E	670.50	572.50	1171.10
15 °N64°E	599.50	ND	1337.00	12°N 88 °E	703.60	450.00	1171.10
19 °N64°E	431.75	ND	1053.25	15°N 88 °E	799.00	510.00	779.80
21 °N64°E	381.25	ND	760.00	18°N 88 °E	913.20	500.00	711.70
				20°N 88 °E	860.23	557.50	688.80
				<u>Near Coastal</u>			
10 °N 75° E	526.75	833.00	489.50	12 °N 81 °E	559.06	635.00	935.19
12 °N 74° E	ND	3249.50	ND	15 °N 82 °E	1025.71	582.50	646.60
15 °N73° E	ND	873.50	ND	17 °N 83 °E	2145.88	597.50	923.02
18 °N70° E	ND	1066.75	ND	19 °N 85 °E	1118.34	935.00	564.36
21 °N67°E	ND	ND	1653.00				

SpIM-Spring intermonsoon; SuM- Summer monsoon; Win- Winter monsoon; FIM-Fall intermonsoon; ND, No data

Table 2. Comparative accounts of primary production ($\text{mg C m}^{-2}\text{d}^{-1}$) in the 0-120 m column in the open ocean and along the coastal stations of Arabian Sea and Bay of Bengal during different seasons. Arabian Sea data derived from JGOFS (India) Programme.

Arabian Sea				Bay of Bengal			
				Seasons			
	SpIM	SuM	Win		SpIM	SuM	FIM
<u>Locations</u>				<u>Locations</u>			
				<i>Open Ocean</i>			
11° N64°E	132.35	773.50	333.00	9° N 88 °E	203.55	220.65	512.85
15 °N64°E	194.45	ND	604.00	12°N 88 °E	215.62	107.18	316.21
19 °N64°E	ND	ND	477.00	15°N 88 °E	201.66	136.48	335.65
21 °N64°E	ND	ND	848.00	18°N 88 °E	155.40	168.32	181.73
				20°N 88 °E	427.32	89.39	184.14
				<i>Near Coastal</i>			
10 °N 75° E	216.65	661.00	ND	12 °N 81 °E	304.73	502.01	244.63
12 °N 74° E	ND	1764.00	ND	15 °N 82 °E	250.00	39.73	196.43
15 °N73° E	ND	384.00	ND	17 °N 83 °E	438.67	328.39	333.93
18 °N70° E	ND	438.50	ND	19 °N 85 °E	469.21	433.85	350.46
21 °N67°E	324.55	ND	765.50				

SpIM-Spring intermonsoon; SuM- Summer monsoon; Win- Winter monsoon; FIM-Fall intermonsoon; ND, No data

Table 3a. Major groups of phytoplankton in the Bay of Bengal during different seasons.

Seasons	Oceanic region		Coastal region	
	species	%	species	%
SuM	<i>Coscinodiscus concinnus</i>	5.19	<i>Skeletonema costatum-</i>	4.48
			<i>Coscinodiscus radiatus</i>	4.78
	<i>Nitzschia angularis</i>	8.87	<i>Chaetoceros coarctatus</i>	4.87
			<i>Nitzschia delicatissima</i>	3.95
FIM	<i>Rhizosolenia styliformis</i>	9.68	<i>Thallasiosira</i> sp	7.09
	<i>Navicula</i> sp	7.17	<i>Navicula</i> sp	4.98
	<i>Thalassionema nitzschoides</i>	6.45	<i>Thallasiosira graviora</i>	4.47
	<i>Rhizosolenia shruvsolei</i>	6.27	<i>Ditylum brightwelli</i>	3.07
SpIM	<i>Navicula</i> sp	21.82	<i>Chaetoceros didymus</i>	17.90
	<i>Navicula distans</i>	5.45	<i>Navicula</i> sp	7.26
	<i>Coscinodiscus</i> sp	5.45	<i>Pseudonitzschia</i> sp	3.64
	<i>Rhizosolenia striata</i>	5.20	<i>Navicula messanensis</i>	3.02
			<i>Chaetoceros curvisetus</i>	5.32
			<i>Rhizosolenia cylindrus</i>	3.99
			<i>Rhizosolenia flaccida</i>	3.02
			<i>Bacteriastrum furcatum</i>	6.53
		<i>Bacteriastrum comosum</i>	6.89	

Table 3b. Predominant Phytoplankton Species in the Bay during different seasons

Seasons	Oceanic		Coastal	
	Species	%	Species	%
SuM	<i>Thalassiothrix longissima</i>	21.02	<i>Thalassiothrix longissima</i>	25.78
	<i>Thalassiothrix frauenfeldii</i>	16.80	<i>Thalassiothrix frauenfeldii</i>	25.75
FIM	<i>Rhizosolenia styliformis</i>	9.68	<i>Thallasiosira</i> sp	7.09
SpIM	<i>Trichodesmium</i> sp	35.15	<i>Chaetoceros didymus</i>	17.90

Table 3a. Major groups of phytoplankton in the Bay of Bengal during different seasons.

Seasons	Oceanic region		Coastal region	
	species	%	species	%
SuM	<i>Coscinodiscus concinnus</i>	5.19	<i>Skeletonema costatum-</i>	4.48
			<i>Coscinodiscus radiatus</i>	4.78
	<i>Nitzschia angularis</i>	8.87	<i>Chaetoceros coarctatus</i>	4.87
FIM			<i>Nitzschia delicatissima</i>	3.95
	<i>Rhizosolenia styliformis</i>	9.68	<i>Thallasiosira</i> sp	7.09
	<i>Navicula</i> sp	7.17	<i>Navicula</i> sp	4.98
	<i>Thalassionema nitzschoides</i>	6.45	<i>Thallasiosira gravida</i>	4.47
	<i>Rhizosolenia shrubsolei</i>	6.27	<i>Ditylum brightwelli</i>	3.07
SpIM	<i>Navicula</i> sp	21.82	<i>Chaetoceros didymus</i>	17.90
	<i>Navicula distans</i>	5.45	<i>Navicula</i> sp	7.26
	<i>Coscinodiscus</i> sp	5.45	<i>Pseudonitzschia</i> sp	3.64
	<i>Rhizosolenia striata</i>	5.20	<i>Navicula messanensis</i>	3.02
	<i>Chaetoceros curvisetus</i>	5.32	<i>Rhizosolenia cylindrus</i>	3.99
	<i>Rhizosolenia flaccida</i>	3.02	<i>Bacteriastrum furcatum</i>	6.53
		<i>Bacteriastrum comosum</i>	6.89	

Table 3b. Predominant Phytoplankton Species in the Bay during different seasons

Seasons	Oceanic		Coastal	
	Species	%	Species	%
SuM	<i>Thalassiothrix longissima</i>	21.02	<i>Thalassiothrix longissima</i>	25.78
	<i>Thalassiothrix frauenfeldii</i>	16.80	<i>Thalassiothrix frauenfeldii</i>	25.75
FIM	<i>Rhizosolenia styliformis</i>	9.68	<i>Thallasiosira</i> sp	7.09
SpIM	<i>Trichodesmium</i> sp	35.15	<i>Chaetoceros didymus</i>	17.90

Table 4. Major groups of mesozooplankton (representing >2% of total in each of 72 samples) during the fall intermonsoon months of September-October 2002.

In oceanic waters	In coastal waters
Copepods	Copepods
Chaetognaths	Chaetognaths
Ostracods	Polychetes
Oikopleura	Ostracods
Euphausids	Oikopleura
Siphonophore	Euphausids
Medusae	Luciferprotozoa
Gastropods	Siphonophore
Pteropods	Foraminifera
Foraminifers	Invertebrate eggs
Invertebrate eggs	
Crustacean nauplii	
Fish larvae	

Table 5. Column integrated living carbon biomass (mg C m^{-2}) of phytoplankton (chl a), Heterotrophic bacteria, meso and micro-zooplankton during different seasons from sampling locations in the 0-120 m for the former two and in the mixed layer depths (MLD) for meso and from 0-200m for microzooplankton

Seasons:	SpIM	SuM	FIM	SpIM	SuM	FIM	SpIM	SuM	FIM	SuM	FIM
Locations											
<u>Open Ocean</u>	<u>Chl a C</u>			<u>Bacterial C</u>			<u>MLD Mesozoo C</u>			<u>microzoo C</u>	
9°N 88°E	670.50	572.50	1171.10	234.59	2083.90	407.45	230.85	2411.15	1231.20	17.98	28.09
12°N 88 °E	703.60	450.00	1171.10	104.90	913.27	386.81	187.76	2346.97	409.37	ND	21.44
15°N 88 °E	799.00	510.00	779.80	85.88	667.82	426.47	615.60	281.38	461.44	21.27	21.98
18°N 88 °E	913.20	500.00	711.70	259.31	1033.65	463.19	2359.80	307.80	307.80	ND	18.52
20°N 88 °E	860.23	557.50	688.80	263.56	1118.81	383.57	666.90	5140.26	307.80	35.06	20.10
<u>Near Coastal</u>											
12 °N 81 °E	559.06	635.00	935.19	179.14	288.68	955.11	168.38	179.55	204.69	22.93	29.07
15 °N 82 °E	1025.71	582.50	646.60	155.65	833.19	534.55	205.20	ND	153.90	29.78	20.93
17 °N 83 °E	2145.88	597.50	923.02	131.03	757.95	925.84	1265.32	641.25	589.95	ND	16.71
19 °N 85 °E	1118.34	935.00	564.36	227.02	684.01	1407.15	2735.83	641.35	215.46	ND	51.68

SpIM-Spring intermonsoon; SuM- Summer monsoon; Win- Winter monsoon; FIM-Fall intermonsoon; ND, no data

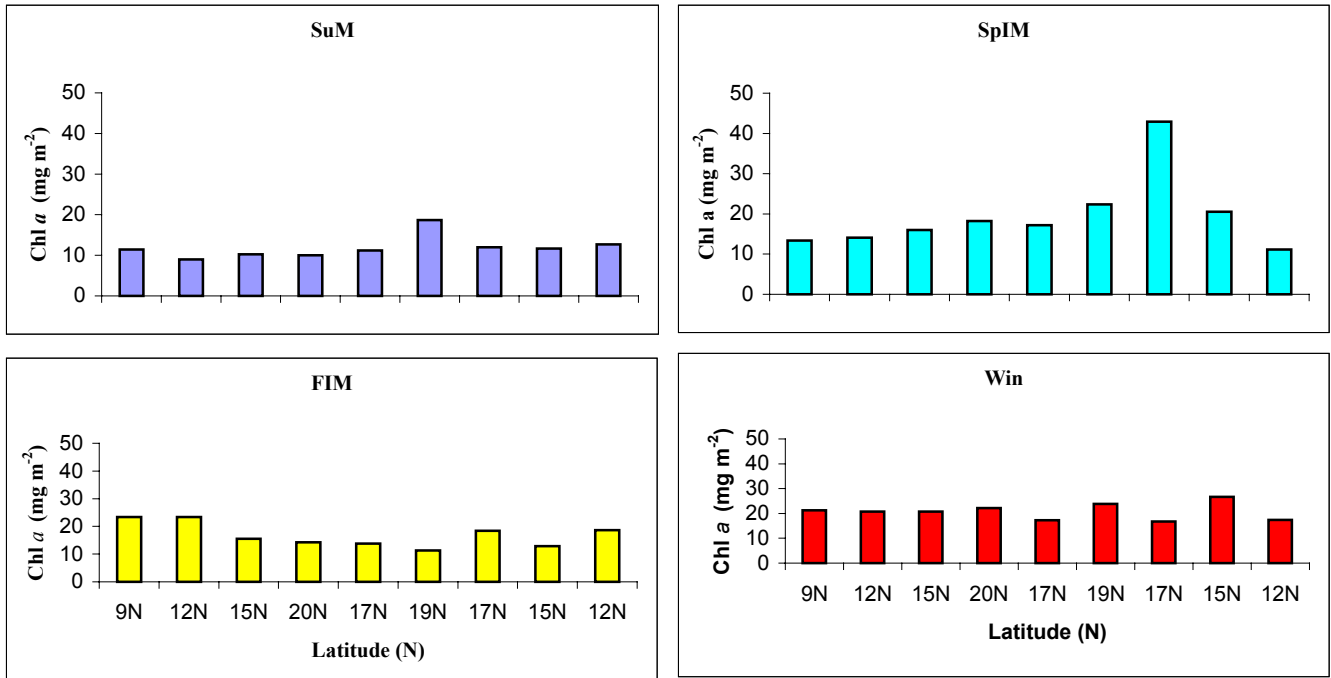


Figure 1. The 0-120 m column integrated Chl *a* (mg m⁻²) in the Bay of Bengal during different seasons (SuM, summer monsoon [July-August 2001]; FIM, Fall intermonsoon [Sept-Oct 2002]; SpIM, spring intermonsoon [April-May 2003] and Win, winter [November-December 2005])

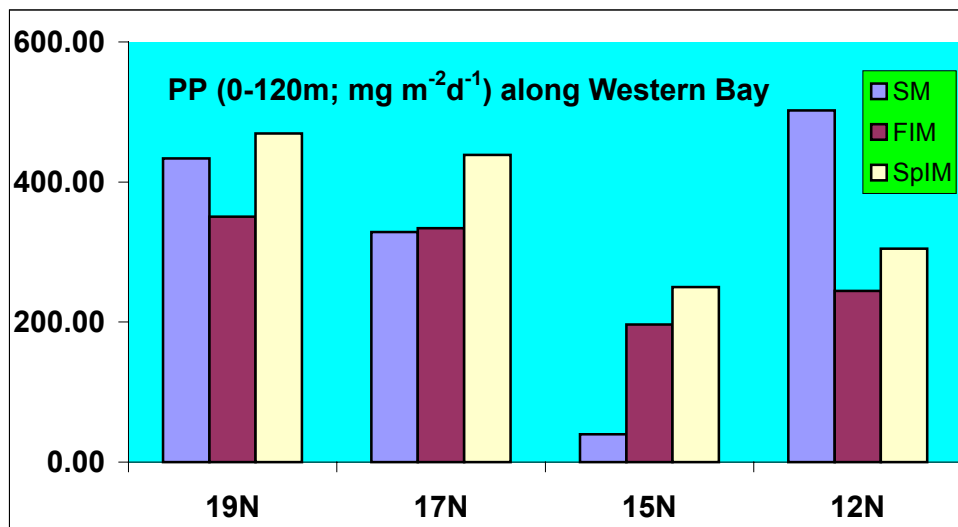
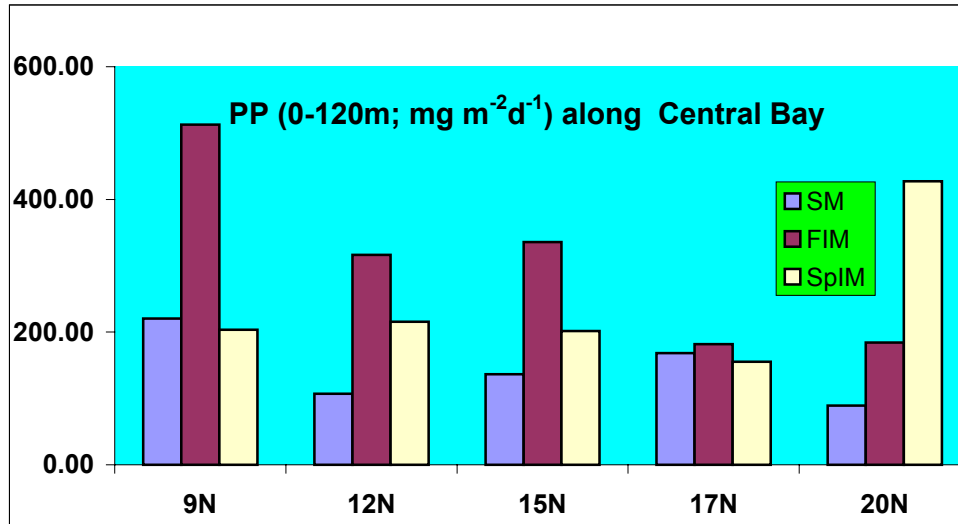


Fig 2. The 0-120 m column integrated primary production rates ($\text{mg C m}^{-2}\text{d}^{-1}$) in the Bay of Bengal during different seasons (SM, summer monsoon [July-August 2001]; FIM, Fall intermonsoon [Sept-Oct 2002]; SpIM, spring intermonsoon [April-May 2003])

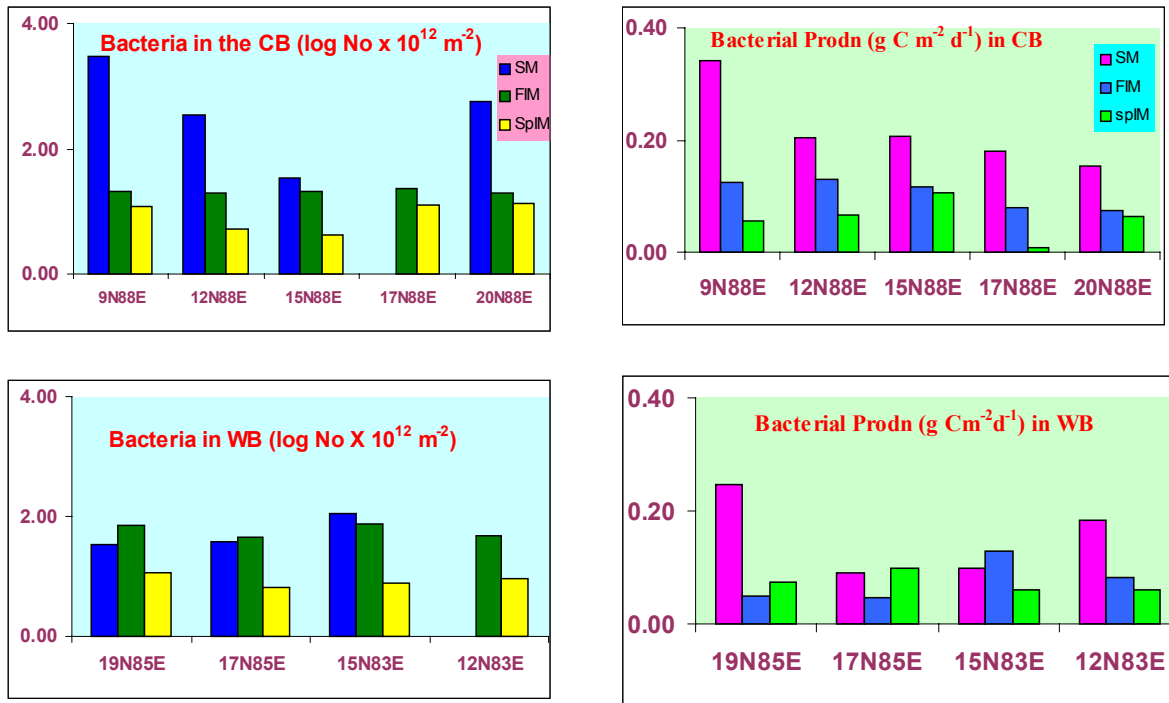


Fig 3. Column integrated (0-120m) bacterial abundance (left panel) and production (right panel) in the Bay of Bengal during different seasons (SM, summer monsoon [July-August 2001]; FIM, Fall intermonsoon [Sept-Oct 2002]; SpIM, spring intermonsoon [April-May 2003]).

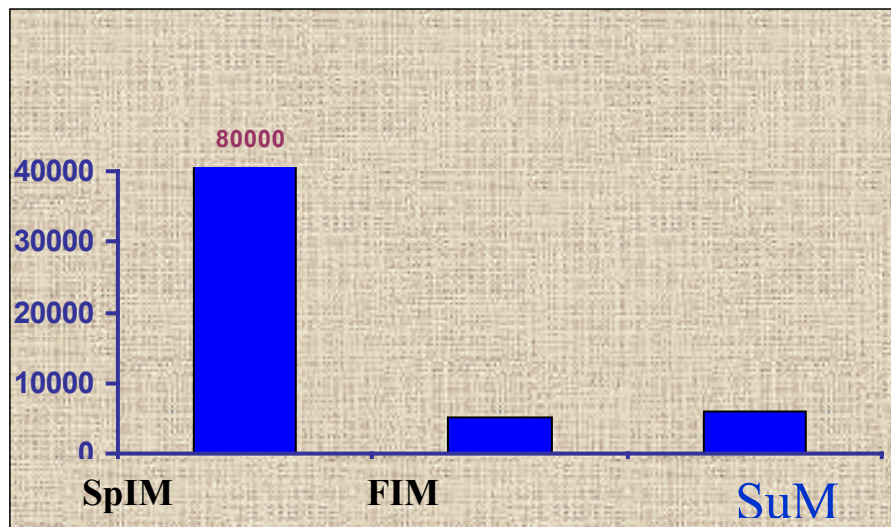


Fig 4. Column integrated microzooplankton (No x 10³ m⁻²) abundance in the Bay of Bengal during different seasons (SuM, summer monsoon [July-August 2001]; FIM, Fall intermonsoon [Sept-Oct 2002]; SpIM, spring intermonsoon [April-May 2003])

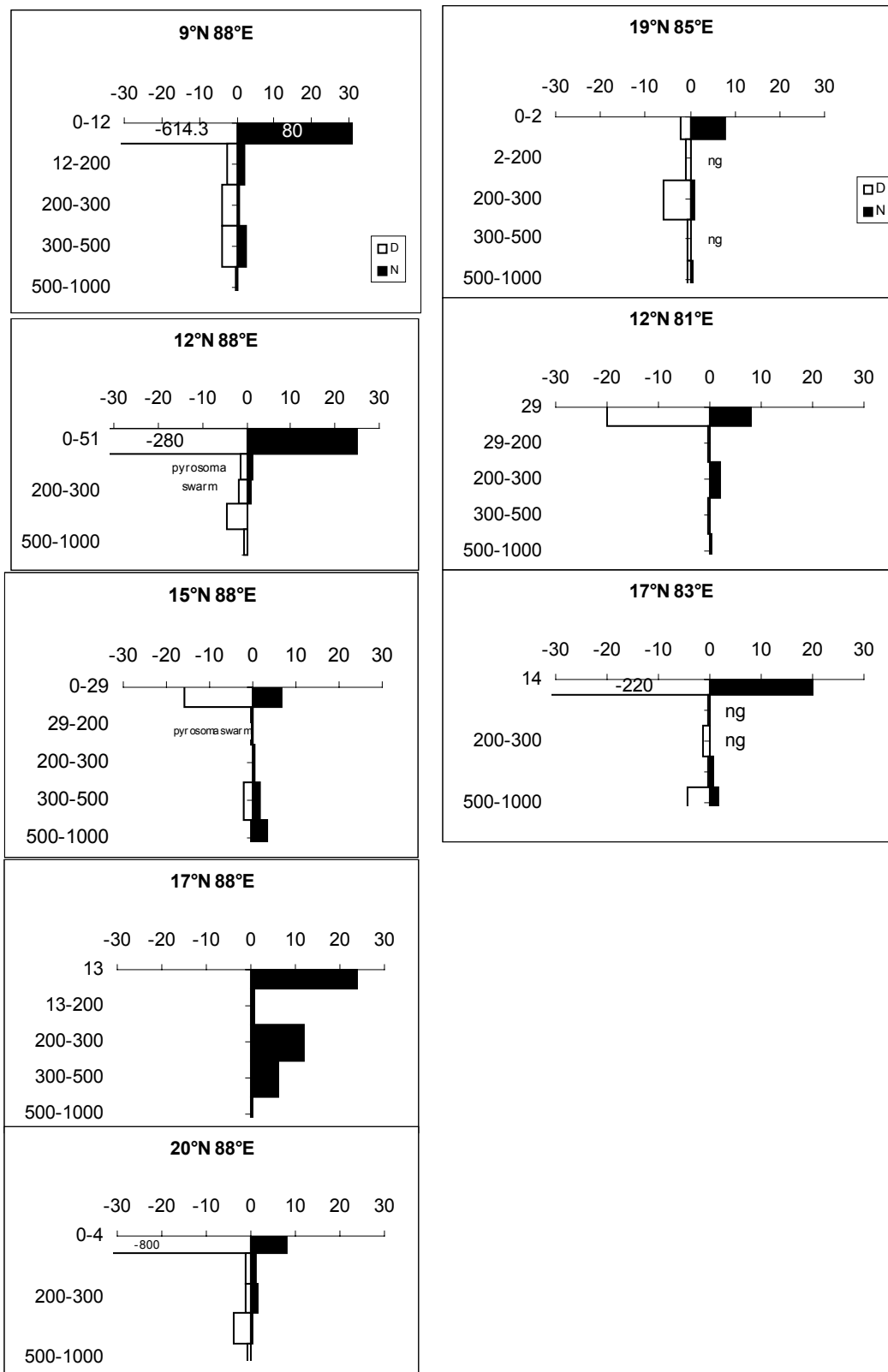


Fig 5a. Biomass in terms of displacement volume (ml.100 m⁻³) of mesozooplankton at different sampling locations during the summer monsoon months of July-August 2001

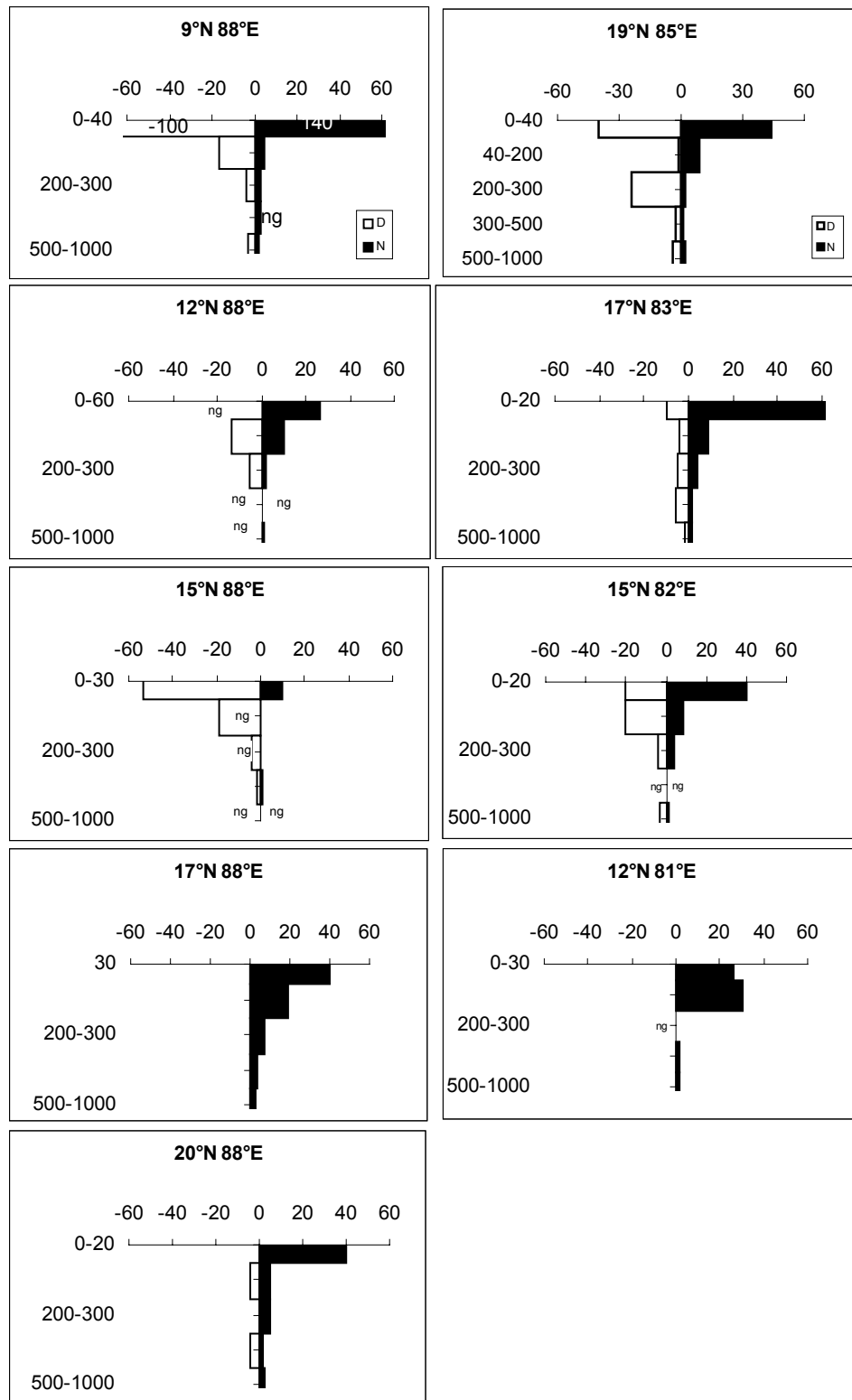


Fig 5b. Biomass in terms of displacement volume (ml.100 m⁻³) of mesozooplankton at different sampling locations during the fall intermonsoon months of Sept-October 2002

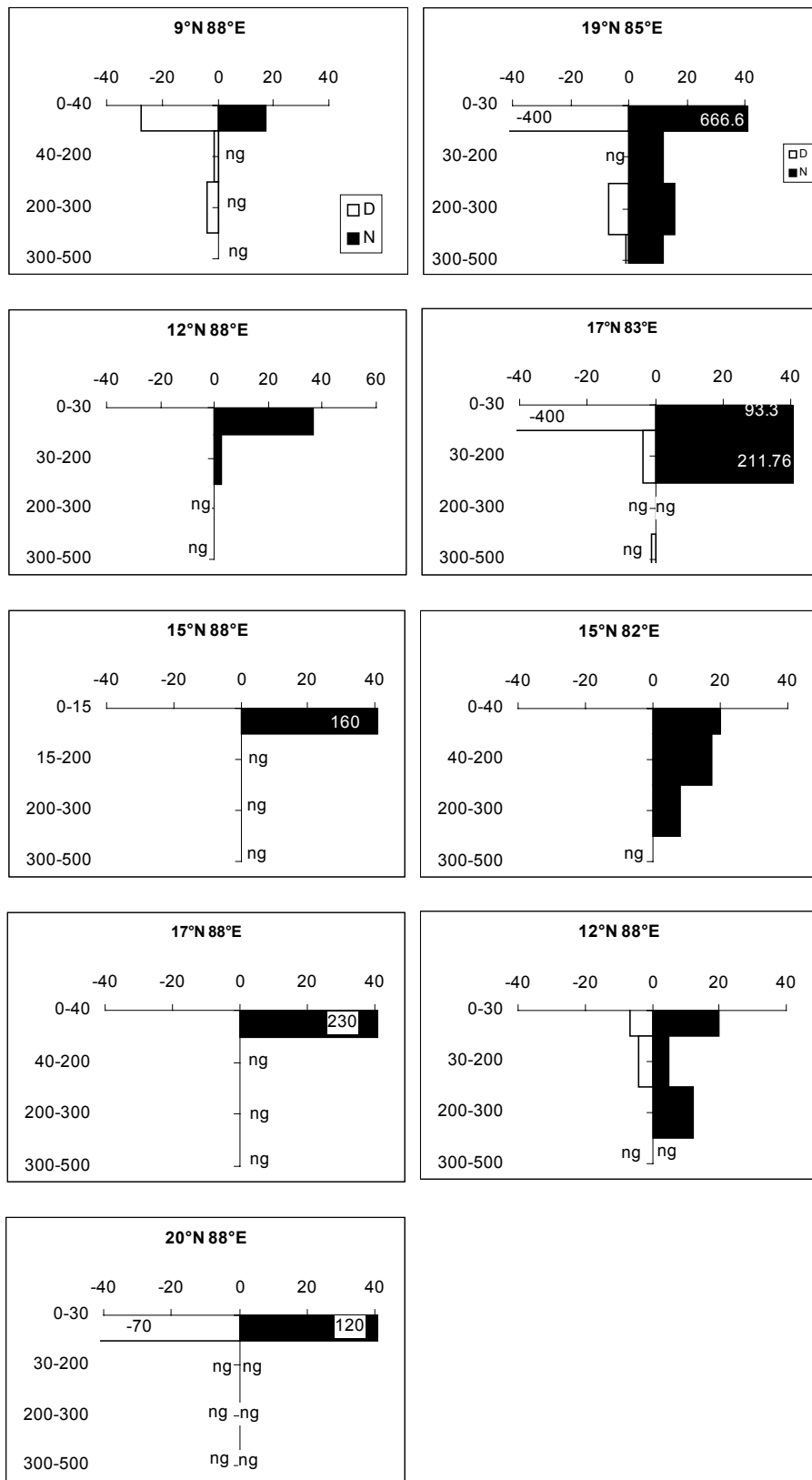


Fig 5c. Biomass in terms of displacement volume (ml. 100 m⁻³) of mesozooplankton at different sampling locations during the spring intermonsoon months of April-May 2003

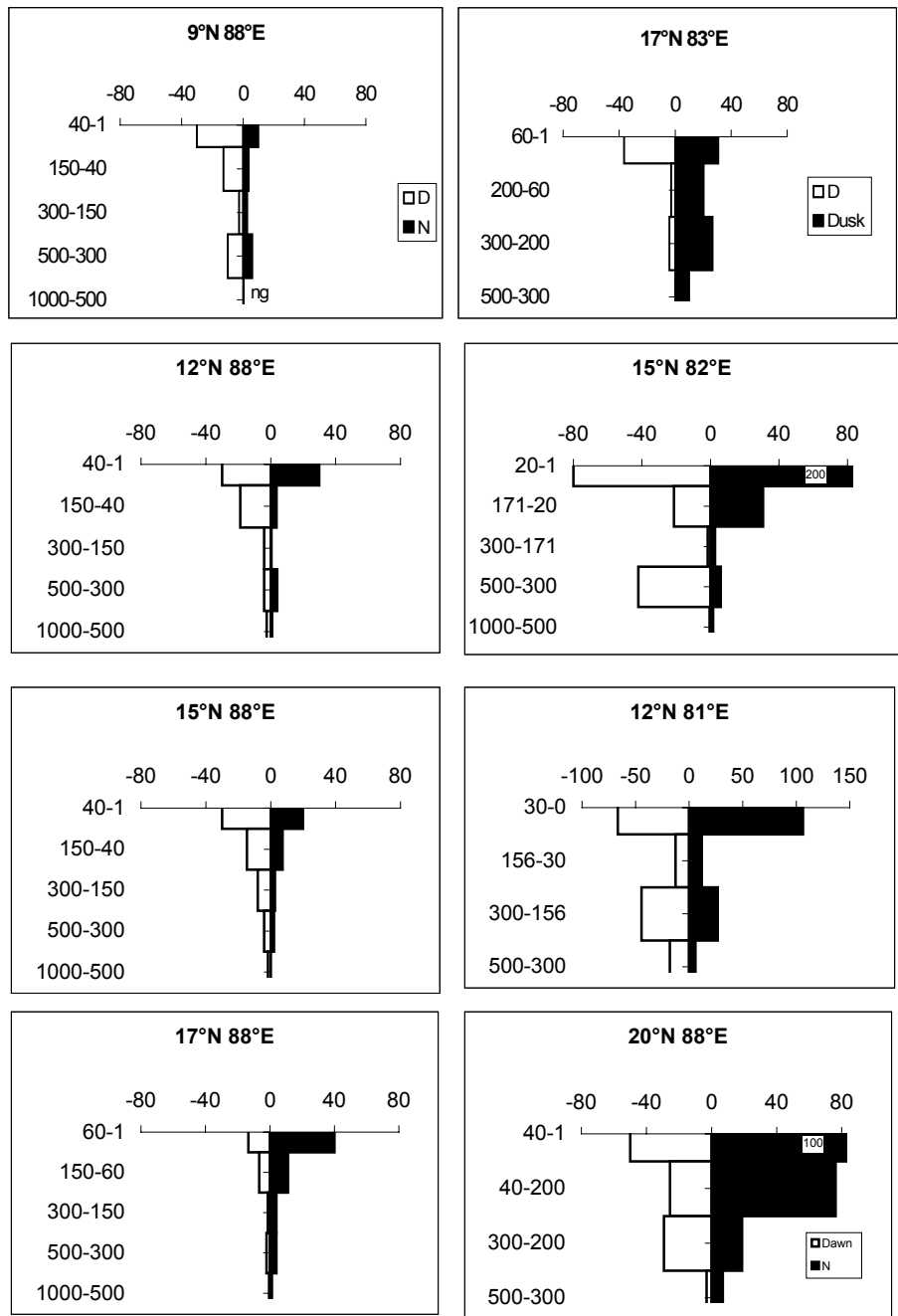


Fig 5d. Biomass in terms of displacement volume (ml.100 m⁻³) of mesozooplankton at different sampling locations during the winter months of November-December 2005

4.2 New production studies

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Introduction

Major international scientific programmes such as JGOFS (Joint Global Ocean Flux Study), aimed at assessing the role of oceans as source/sink of atmospheric carbon dioxide, concentrated mostly on highly productive regions of the oceans, e.g., Arabian Sea. Intense upwelling during summer and convective mixing due to surface cooling in winter enhance the productivity of the Arabian Sea, whereas the Bay of Bengal is less productive because of cloud cover and stratification of the surface layers by copious freshwater discharge from rivers draining the sub-continent, which inhibits vertical mixing and thus supply of nutrients from below. Although there is some seasonal and geographical variability, the typical average productivity in the Arabian Sea is $\sim 800 \text{ mg C m}^{-2} \text{ d}^{-1}$, whereas in the Bay it is about $300 \text{ mg C m}^{-2} \text{ d}^{-1}$, despite comparable numerical abundances of phytoplankton in both these regions. In contrast, sediment trap data show that on the average, the annual downward flux of organic carbon (C_{org}) is roughly comparable in both the regions. One explanation of this paradox is that in the Bay, organic carbon is ballasted into the deep by aggregating with either high lithogenic flux derived from rivers or by minerals, e.g., carbonates. However, the annual lithogenic flux in the Bay decreases sharply from the north to the central (shallow) trap (21.89 g m^{-2} to 9.37 g m^{-2} , by 57%), whereas the organic carbon flux does not show a corresponding reduction (by 26%). Further, time series data from two shallow traps in the north ($17^\circ 27' \text{ N}$ and $15^\circ 32' \text{ N}$) show that the annual lithogenic flux decreased from 14.5 to 8.7 g m^{-2} (by 40%), carbonate fluxes comparable (12.5 to 13 g m^{-2}), while organic matter flux decreases from 5.6 to 4.3 g m^{-2} (by 23%). While there may be some merit in the ballast hypothesis, independent estimates of new production based on nitrogen uptake could help resolve this paradox, because, under steady state, new production is considered theoretically equal to the export production. Regions with high new production have high export production, leading to increased downward flux of organic matter, and thus can be very effective in removing excess atmospheric CO_2 .

Results

We present in Table 1 the results of new (nitrate uptake) and regenerated production (ammonium and urea uptake) estimated using ^{15}N tracer (99 atom% enriched) technique in the Bay of Bengal. Sampling was performed at nine different stations onboard ORV Sagar Kanya during two seasons (cruise SK 182, Sep-Oct. (post monsoon) 2002, and SK191, Apr-May. (pre-monsoon), 2003). The analysis was performed using a CarloErba elemental Analyzer interfaced via Conflo III to a Finnigan Delta Plus mass spectrometer using a technique for sub-microgram level ^{15}N determination. All water samples were processed in duplicate, and the maximum difference in the measured particulate organic nitrogen of duplicate samples is found to be $< 10\%$. The coefficient of variation in ^{15}N atom% measurement is less than 1% for samples that used nitrate or urea substrates while 3.4% for those using ammonium (see also caption to Table 1).

The 'f' ratio, defined as the ratio of new to total production (equivalently, the ratio of nitrate uptake to the total uptake), is in general very high (mean ~ 0.61), regardless of season and the proximity to the coast (Table 1. This is significantly higher than the values (mean < 0.3) reported

for the highly productive northwestern Arabian Sea. Using the Redfield ratio (C/N) of 6.6, we convert the total nitrogen uptake to carbon uptake; the total productivity in Bay of Bengal varied from 90 to 870 mg Cm⁻²d⁻¹ during Sep-Oct. 2002, with an average value of 316 mg Cm⁻²d⁻¹. These are somewhat higher than productivity measured by ¹⁴C tracer method during an earlier cruise (40 to 502 mg Cm⁻²d⁻¹) during the peak summer monsoon (July, 2001). The reason could be two fold: first, during the post-monsoon season the mean cloudiness reduces (i.e., more light available for photosynthesis), and second, the frequent cyclones stir up the surface and thus supply nutrients from below. Chlorophyll a concentrations in the surface always exceeded 0.2 mg m⁻³, and are higher than July (2001) values. Table 1 reveals that the mixed layer depths were generally higher for open ocean (SK 182, odd rows) than the coast; station PP2 had the highest mixed layer depth and also the highest total productivity.

Table 1. Column integrated uptake rates (mg-atom N m⁻² d⁻¹) in coastal (marked with * and open Bay of Bengal during Sep.-Oct. 2002 (cruise SK 182, odd rows) and Apr-May, 2003 (cruise SK 191, even rows). Four to six depths were sampled at each station. Measured light intensities were uniformly less than 1% at ~60 m depth (SK182) and at 60-100m (SK 191). Blanks (atom% ¹⁵N) were 0.368 ± 0.001, 0.397 ± 0.011 and 0.411 ± 0.036, respectively, for nitrate, ammonium and urea experiments, all data are blank-corrected. Three standards IAEA-NO-3 (KNO₃, no. 213), IAEA-N-2 ([NH₄]₂SO₄, no. 342), and USGS-32 (KNO₃) gave values 0.3674 ± 0.0009 (n = 37), 0.373 ± 0.004 (n = 72), and 0.429 ± 0.005 respectively. Column nitrate in the second cruise is generally higher because the depth of the photic zone (over which the values are integrated) was higher.

Stn.	Lat (°N)	Long (°E)	Uptake rate (mg-at N m ⁻² d ⁻¹)				f-ratio	mixed layer depth (m)	Surface	Column
			Nitrate	Ammonium	Urea	Total			Nitrate μM	Nitrate μmol.m ⁻²
PP1	8° 59' 58.9"	87° 58' 43.1"	0.43	0.32	0.49	1.25	0.34	40	0.14	348
			0.99	0.67	0.44	2.1	0.47	15	0.4	863
PP2	11° 58' 57.9"	87° 57' 58.2"	8.84	0.81	1.32	10.98	0.8	60	0.04	90
			3.02	0.91	0.94	4.88	0.62	12	0.2	660
PP3	15° 0' 9.3"	87° 58' 24"	1.43	0.79	1.14	3.37	0.42	30	0.08	69
			1.82	1.07	1	3.9	0.47	37	0.4	626
PP4	17° 56' 33.1"	87° 54' 38.6"	1.53	0.28	0.87	2.68	0.57	30	0.08	369
			10.15	1.95	1.07	13.18	0.77	40	0.2	283
PP5*	20° 0' 0.4"	88° 0' 1.8"	2.13	0.48	0.96	3.58	0.6	10	0.11	435
			2.47	1.03	0.6	4.1	0.6	30	0.2	773
PP6*	18° 59' 44.8"	85° 30' 4.8"	4.48	0.48	0.99	5.96	0.75	10	0.2	59
			12.94	1.08	0.95	14.97	0.86	20	0.8	1044
PP7*	16° 59' 29.7"	83° 30' 3"	3.87	0.47	1.12	5.47	0.71	10	0.17	566
			7.87	0.96	0.57	9.4	0.84	20	0.2	1622
PP8*	15° 0' 20"	81° 29' 47"	0.16	0.47	0.84	1.48	0.11	5	0.11	252
			9.18	1.82	1.59	12.59	0.73	45	0.2	113
PP9*	11° 59' 37.3"	81° 0' 9.8"	0.62	0.28	0.25	1.16	0.54	10	0.21	626
			11.08	1.78	1.99	14.85	0.75	30	0.50	490

Furthermore, in 2002 the monsoon was somewhat weaker (80% of long term mean rainfall over India), leading possibly to less than normal stratification of the surface Bay. During the pre-monsoon cruise, 2003, (SK 191) the total production varied from 167 to 1190 mg C m⁻²d⁻¹, significantly higher than that of the monsoon and post-monsoon seasons, especially in the coastal stations; the reason is increased mixed layer and photic zone depths, and increased nutrients brought by the northward flowing East India Coastal Current.

There is a very significant correlation between new (y) and total production (x) (**Fig. 1**): $y = (0.88 \pm 0.03)x - (0.89 \pm 0.19)$ (coefficient of determination, $r^2 = 0.99$) in the Bay of Bengal during SK182 and $y = (0.87 \pm 0.04)x - (1.12 \pm 0.46)$ ($r^2 = 0.99$), during SK 191. When the data for both seasons are regressed as a whole, we get $y = (0.86 \pm 0.03)x - (0.91 \pm 0.20)$ ($r^2 = 0.99$). Data for the Arabian Sea also show such a correlation, but with some scatter: $y = (0.33 \pm 0.04)x - (0.36 \pm 0.44)$ ($r^2 = 0.86$). Interestingly, in both the seas, the x-intercept, i.e. minimum amount of regenerated production in the total absence of extraneous nitrate supply is ~ 1 mg-at. N m⁻² d⁻¹ (equivalently ~ 80 mg C m⁻² d⁻¹). The f-ratio ($= y/x$) can be expressed as $\alpha(1-1/x)$ (as the slope and intercept are roughly equal in magnitude, within errors, in each case), where x is the total production and α is the slope of the straight-line in(x, y) plot. It is apparent that when x tends to large values, there is a limit to the f-ratio, given by the slope, α . Thus, available limited data suggest that in the Bay of Bengal, the f-ratio can be as high as 0.86 while in the Arabian Sea it can be at best ~ 0.33 .

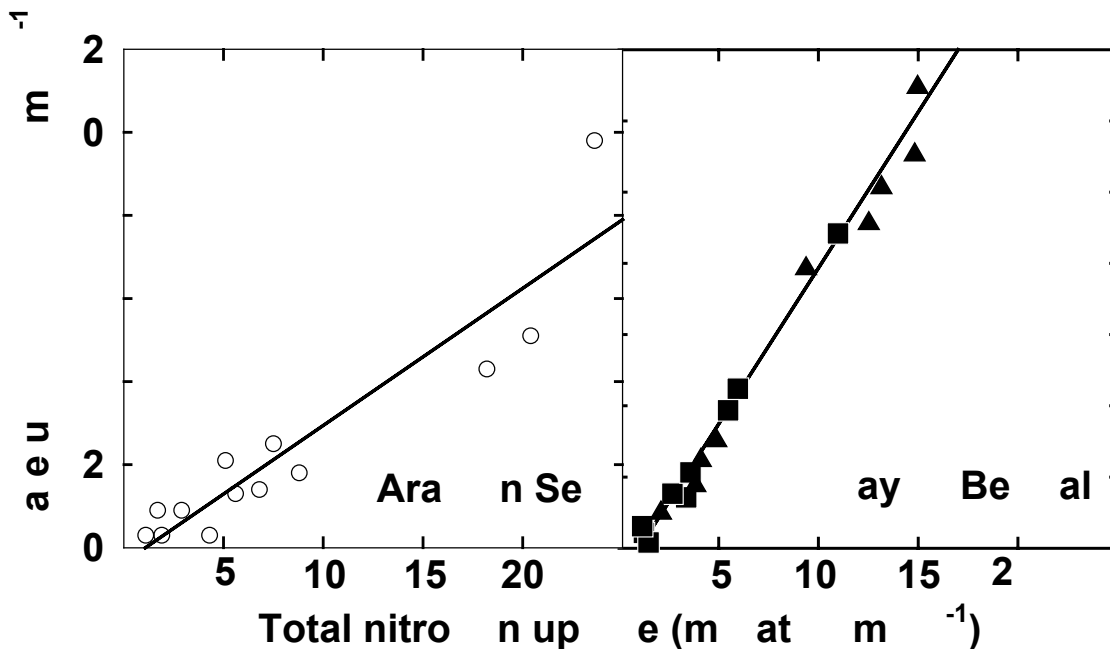


Figure.1 Relationship between total and new production in the Bay of Bengal (filled triangles, cruise SK 191, Apr.-May 2003; filled squares, SK 182, Sep.-Oct. 2002) and the Arabian Sea (open circles; data from ref. 24; experimental techniques are the same, and urea uptake has been taken into consideration for the calculation of f-ratio, as in this study). Each data point is based on a total of six independent measurements.

What is the source of excess nitrate causing these high values of new production in the Bay? One possibility is that the river water discharge ($1.6 \times 10^{12} \text{ m}^3/\text{y}$) supplies nitrate from the adjacent land. Measurements from estuarine region of Godavari and the adjoining shelf region of the Bay show that the annual flux of nitrate is ~ 3900 tons. Similar or higher fluxes are expected from the Ganga-Brahmaputra rivers system (data lacking). The second possibility is the supply of nitrate from below. The shallow nitracline in the Bay of Bengal might have allowed the nitrate to come up to the surface, especially when aided by churning due to cyclonic winds in the post-monsoon season. Uptake of nitrate in shallow nitracline conditions has also been observed elsewhere. A third possibility is sub-marine ground water discharge, which can be a rich source of nitrate. The measured values of surface nitrate are in the range 0.1 to $0.8 \mu\text{M}$ (Table 1).

Regardless of the source, it is evident that the supplied nitrate is immediately taken up by the phytoplankton. This is supported by our measurements of $\delta^{15}\text{N}$ of the planktons of the Bay: (i) most values in open ocean stations are comparable to the $\delta^{15}\text{N}$ of deeper nitrate ($\sim 6 \text{ ‰}$), implying that the phytoplanktons take up nitrate without fractionation. This can happen only when the available nitrate pool is small and is quickly used up. (ii) values in coastal stations average $\sim 3 \text{ ‰}$ indicating terrestrial influence. Overall, it appears that both terrestrial and marine sources of nitrate are available to the phytoplankton in the Bay, and the nitrate is consumed as soon as it becomes available. For the phytoplanktons to synthesize the necessary enzymes to achieve this, the nitrate input needs to occur frequently. This happens by the perennial river/ground water discharge, complemented by mixing of the ocean due to frequent cyclones in the post-monsoon season.

Direct comparison of productivity measurements with sediment trap data is marred by the inherent difference in the time scales (shorter than a day versus longer than a week). While this problem cannot be solved completely, we measured productivity on widely separated stations spread over a month each, under different atmospheric and oceanic conditions and obtained consistently high new production. Further the bimonthly C_{org} values from the shallow sediment trap data show that pre-monsoon values (0.68 g Cm^{-2}) are about twice the post-monsoon values (0.30 g Cm^{-2}) in the Bay. Our new production measurements confirm this (a mean of 526 versus $208 \text{ mg Cm}^{-2} \text{ d}^{-1}$, respectively), indicating that about 2 to 3% of C_{org} exported from the photic zone reaches the depth of 1000 m .

Conclusions

We have shown that even moderately productive oceanic regions such as the Bay of Bengal, may be capable of high new production, and thus can be at least as efficient in removing the atmospheric CO_2 as areas of high total production. This study underscores the need for more new production measurements in different oceanic regions hitherto considered low or moderately productive.

5. Biochemistry Programme

5.1 Biogeochemical cycling of Carbon & Nitrogen in the Bay of Bengal

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Objectives

- (1) To understand the variability in nutrient input into surface layer, from run-off and upwelling, and its influence on the productivity patterns.
- (3) Seasonal and spatial variability in the overall CO₂ air-sea exchange balance in the Bay of Bengal.
- (4) To understand factors controlling the distribution of carbon components such as DOC and TEP and their role in carbon cycling.
- (5) The role of cyclones and remote forcing in the spatio-temporal variability of the water column in terms of nutrients and productivity.

Introduction

The Bay of Bengal, one of the two northern arms of the Indian Ocean, has distinctive characteristics. A massive freshwater discharge of 1.6×10^{12} m³/year from the seven major rivers (Subramanian, 1993) together with precipitation, results in an excess freshwater input over evaporation (Venkateshwaran, 1956) of 1500×10^9 m³ leading to a positive water balance in the bay (Ramanathan and Pisharoty, 1972). A freshwater discharge of such a magnitude in a small area causes strong stratification in the upper layers. This slows down the rate of exchange of nutrients between the nutrient-enriched deep waters and the euphotic layers. However, there are conflicting reports on the productivity of the bay. One of the questions needs to be addressed is the sources and extent of nutrient supply into the bay.

Along with the enormous influx of freshwater, the Bay of Bengal receives 1387×10^6 tons of suspended solids annually (Subramanian, 1993). Organic matter associated with this massive discharge of freshwater and suspended solids, is expected to contribute significantly to the carbon and nitrogen pools of the Bay of Bengal and may have a control over their biogeochemical cycling. The rate of organic matter decomposition within the water column is reported to be low due to the sedimentation of organic matter ($2.04\text{-}3.59$ g C m⁻²yr⁻¹; Ittekkot *et al.*, 1991) consequent to its incorporation into the rapidly sinking terrigenous material in the Bay of Bengal (Kumar *et al.*, 1998).

The near equatorial oceans are generally found to be sources of atmospheric carbon dioxide. In agreement with this we found that the Arabian Sea acts as a perennial source of atmospheric carbon dioxide (Sarma *et al.*, 1998); a result of our effort under JGOFS (India)-Arabian Sea Programme. However, the freshwater discharge into the bay seems to make this region a seasonal sink (Kumar *et al.*, 1996). Nevertheless, this exchange process is not clearly known. On the other hand, the water column chemistry of carbon is only little known (George *et al.*, 1994). The north-south gradients in carbon dioxide, as occurred in the Arabian Sea, are not evident. Moreover, there is no information on the dissolved organic carbon in the Bay of Bengal despite the facts that rivers pour in large quantities of dissolved organic matter. No active denitrification is found to occur even in the sub-oxic waters of the Bay of Bengal (Naqvi *et al.*, 1994; Rao *et al.*, 1994). In view of this, it is essential to study and understand the carbon cycle in detail in the bay where land-ocean-atmosphere interacts vigorously, the extent of which varies with seasons. In order to

understand the physical and biological controls operating on the biogeochemical cycling of carbon and nitrogen in the Bay of Bengal, following issues were addressed:

Material and Methods

Sampling was carried out at 24 stations along two transects on board ORV Sagar Kanya during four seasons;- Southwest monsoon (July-August, 2001), fall intermonsoon (September-October, 2002), spring intermonsoon (April-May, 2003) and winter monsoon (December 2005-January 2006) as shown in figure 1. Fourteen stations were occupied between 7°N to 20°N in the open ocean transect along 88°E and 10 stations were occupied along the western margin from 11°N to 20°N. Samples were collected at discrete depths in the upper 1000 m water column using 10/30 litres GO-Flow bottles attached to a rosette connected to Sea Bird CTD. Measurements of dissolved oxygen, pH, total carbon dioxide (TCO₂), Total organic carbon (TOC), transparent exopolymer particles (TEP) and nutrients (nitrate, nitrite, phosphate and silicate) were carried out. Samples were collected for dissolved oxygen, and nutrients in glass and plastic bottles, respectively. Dissolved oxygen was analysed by Winkler titration. Nitrate, nitrite, phosphate and silicate were estimated by autoanalyser (skalar) during the southwest monsoon and winter cruise and by following the manual methods of Grasshoff et al. (1983) during the other two seasons. There was good agreement in the precision between the two methods. The detection limits for nitrate, phosphate and silicate were 0.1, 0.03 and 0.5 $\mu\text{mol L}^{-1}$ respectively. Total carbon dioxide (TCO₂) was analysed by coulometric method (George *et al.*, 1996). PH was estimated by multiwavelength spectrophotometric technique using cresol red indicator (Byrne & Breland, 1989) and was utilized for the computations of pCO₂ from total carbon dioxide. Total organic carbon (TOC) was measured by the high temperature catalytic oxidation method using total organic carbon analyzer while the transparent exopolymer particles (TEP) were estimated by a spectrometric technique involving Alcian blue staining (Passow and Alldredge, 1995).

Results and discussion

Dissolved oxygen

Oxygen levels showed the influence of eddies in the three seasons by the upward tilting of the isolines in the eddy regions (Fig.2 a,b,c) . This resulted in a water mass with low oxygen levels in the surface layer. During Southwest monsoon, intense oxygen minimum ($\leq 10 \mu\text{mol L}^{-1}$) extends horizontally from about 80 m in the north to about 120 m around 11°N and is seen upto about 600 m mostly confined to the north of 15°N. The intermediate waters towards the south of 13-15° N show relatively higher oxygen levels (15-35 $\mu\text{mol L}^{-1}$) perhaps due to the penetration of Arabian Sea high salinity water into the central Bay. The deeper layer between 400 to 600 m also showed the intrusion of waters with relatively higher oxygen content, which is identified as the high salinity Indian Equatorial Intermediate Waters. Below 600 m the oxygen levels gradually increase upto 1000m.

The eddy in the northern region appears to be well developed during fall intermonsoon season. The oxygen minimum layer is almost similar to that during the southwest monsoon and the intermediate and deeper waters are seen to be under the influence of high salinity water. During spring intermonsoon, the upper layer upto about 40 m shows relatively uniform oxygen content perhaps due to the isohaline structure of this water mass. Towards 19 to 20°N however, the oxygen content is significantly lower due to the upheaval of the subsurface water mass in this

region. The intense oxygen minimum layer is reduced during this season and mostly confined to the northern region between 15 to 20°N. A narrow band of near suboxic waters ($\leq 5 \mu\text{mol L}^{-1}$) is seen around 19 to 20°N between 60 to 200 m and at 15°N between 100 to 120 m. The intermediate and deeper waters do not show the pattern of oxygen distribution as seen in the other two seasons perhaps due to the absence of incursion of high salinity waters at this depth during this season.

The displacement of the water mass due to physical pumping along the western margin (Fig.2d,e,f) is seen at around 17°N in all the three seasons.. The minimum in oxygen is heaved up from 120 m to shallower depths with pockets of suboxic waters between 60 to 100 m at 17° N. The minimum oxygen layer is thicker and spreads from south to north. There is also a core of suboxic water seen in this region between 100 to 400 m to the north of 17°N. In the deeper waters the oxygen minimum extends upto 500 m. During spring, the minimum oxygen layer is reduced and extends from about 250 m at 13°N to about 60 m at 17°N. However, the core of suboxic waters prominently seen in the eddy region during the southwest and fall season is absent during spring intermonsoon. During winter season (Fig. 3) dissolved oxygen levels varied from $215 \mu\text{mol L}^{-1}$ at the surface which gradually decreased to $20 \mu\text{mol L}^{-1}$ at 120 m. Lowest concentration of $15 \mu\text{mol L}^{-1}$ was observed between 16 to 20°N in the depth range of 200 to 600m. There was a gradual increase in oxygen levels below this depth upto 1000m. The eddy observed at 10°N elevated subsurface low oxygen waters to shallower depths. The influence of eddy was not prominent along the western margin. However, sinking of the water mass with relatively higher oxygen was observed between 17 to 18°N. Towards the south a weak eddy signature was observed between 60 to 100 m with an elevation of low oxygen levels to shallower depths. A core of low oxygen is observed in the central region of the western margin between 14 to 17° N around 100 to 150 m.

Nutrients

The distribution of nitrate during different seasons in the open ocean and the western margin is shown in Fig. 3 (a,b,c).& Fig. 4. The shoaling up of the subsurface waters around 9 to 10°N and around 19°N helped in the pumping of nutrients to the upper layers in the euphotic zone in the three seasons. However, during the SW monsoon, the wind forcing could not erode the stratification caused by the spreading of immense discharge of fresh water by the Ganges, Brahmaputra and Irrawady rivers in the north thereby limiting the availability of nitrate to a depth of about 20 m. The fresh water influx in the north does not appear to make a significant contribution to nitrate levels in the surface waters. The shoaling up of the waters with higher nitrate content appears to have improved the primary productivity in the eddy region.

There was addition of nitrate from the fresh water influx in the north during fall intermonsoon. During spring intermonsoon, the oscillations in the nitrate isolines indicate weaker physical forcings in this season compared to the other two seasons. The 40 m deep mixed layer was also found to be oligotrophic.

The western margin showed the dominance of physical forcings in providing nitrate to shallower depths with the shoaling of the isolines around 17°N during the southwest monsoon. There was significant contribution of nitrate from the fresh water input by Mahanadi and Godavari rivers in the northern region. However the southern region was devoid of nitrate upto 40m. During spring intermonsoon, the distribution of nitrate was similar to that in the open ocean. However, the displacement of the water mass at 17°N supplied the nitrate in the surface layer upto 10 m.

Towards the south, though the nitrate deficient layer deepened to 60 m the column productivity was significantly high.

The distribution of phosphate in the open ocean during the three seasons showed a trend similar to nitrate barring some major differences. There was no contribution of phosphate in the northern region through the fresh water influx during the SW monsoon. During fall intermonsoon phosphate concentration in the range of 0.1 to 0.4 $\mu\text{mol L}^{-1}$ was present in the surface layer from south to north whereas during the spring intermonsoon 0.2 $\mu\text{mol L}^{-1}$ of phosphate was observed in the surface layer towards the south between 7 to 10°N. Along the western margin the fresh water addition of phosphate in the northern region during SW monsoon was around 0.4 $\mu\text{mol L}^{-1}$ whereas towards the south, the upper layer upto 40 m was devoid of phosphate. During the fall intermonsoon though the top layer was devoid of nitrate; phosphate was present at levels ranging from 0.2 to 1.2 $\mu\text{mol L}^{-1}$ from south to north. Relatively higher levels of phosphates in the surface layer in the open ocean as well as along the western margin during this season may be the result of the contribution from fresh water due to the leaching of the soil phosphates in the north and the upheaval of the water mass from the sea. During the spring intermonsoon, unlike the open ocean the surface layer in the north showed 0.1 to 0.3 $\mu\text{mol L}^{-1}$ of phosphate which appears to be the contribution from the riverine fresh water. The intermediate and deeper waters showed gradually increasing phosphate levels upto 1000 m.

Silicate follow similar pattern of distribution in the open ocean as that of nitrate with significant amounts of silicates available at shallower depths in the eddy region during the three seasons. The contribution from fresh water discharge in the northern region was upto 2 $\mu\text{mol L}^{-1}$ during the SW monsoon. The deepening of the mixed layer was also seen in the silicate distribution during the spring intermonsoon with surface silicate concentration upto 2 $\mu\text{mol L}^{-1}$. The influence of eddy at 17°N was observed in all the three seasons along the western margin. Fresh water input at 20°N resulted in the silicate concentration of about 9 $\mu\text{mol L}^{-1}$ at the surface. During the fall intermonsoon, besides the other salient features, silicate of 10 to 19 $\mu\text{mol L}^{-1}$ were added at the surface between 19° to 20° N through the riverine fresh water flow whereas towards the south it was about 2 $\mu\text{mol L}^{-1}$. During spring intermonsoon the fresh water inputs of silicate in the north were negligible and the 2 $\mu\text{mol L}^{-1}$ isoline was seen at the surface around 17 to 18°N. The deep mixed layer of 60 m was also seen in the silicate distribution. The intermediate and deeper layers showed increasing silicates upto 1000m.

During winter season distribution of nutrients (fig.5, nitrate) showed oligotrophic conditions upto 40 m from south to north. Presence of eddy could be seen around 10 to 11°N with nutrients higher than the ambient levels at shallower depths. The variability of nutrients along the western margin showed oligotrophic conditions upto 40 m between 17 to 20°N. There was also elevation of nutrients to shallower depths at around 15°N. However, phosphate levels of 0.2 to 0.3 $\mu\text{mol L}^{-1}$ was observed in the upper 20 m in the offshore as well as western margin regions. The distribution of silicates also confirmed the presence of eddy at 10°N in the open ocean with an elevation of silicates levels to shallower depths. The surface layer upto 40 m showed a concentration of 1-2 $\mu\text{mol L}^{-1}$ of silicates in the open ocean whereas the western margin showed silicate levels ranging from 3-6 $\mu\text{mol L}^{-1}$ between 11 to 17°N and at 20°N in the upper 40 m.

Carbon dioxide

Total carbon dioxide (TCO₂) levels varied from 1650 to 2200 $\mu\text{mol L}^{-1}$ in the upper 120 m water column during the southwest monsoon in the open ocean with the minimum concentration being in the less saline waters in the north. During fall intermonsoon the surface waters showed TCO₂ levels of 1500 $\mu\text{mol L}^{-1}$ around 17°N which increased to 2100 $\mu\text{mol L}^{-1}$ around 120 m. Along the western margin, the surface water TCO₂ levels ranged from 1700 $\mu\text{mol L}^{-1}$ in the low salinity region in the north to 1900 $\mu\text{mol L}^{-1}$ towards the south during the southwest monsoon. During fall season lowest concentration of 1500 $\mu\text{mol L}^{-1}$ of TCO₂ was observed in the north, which increased to around 1900 $\mu\text{mol L}^{-1}$ towards the south in the surface waters. The concentration of TCO₂ was 2200 $\mu\text{mol L}^{-1}$ around 120 m. During the winter monsoon the TCO₂ values in the open ocean varied from 1790-2190 $\mu\text{mol L}^{-1}$ in the upper 120 m. TCO₂ levels of 1890 $\mu\text{mol L}^{-1}$ were elevated from ambient 60 m to surface at around 9°N and from 60 m to 40 m at around 17°N under the influence of eddies. Along the western margin, the surface waters showed lower TCO₂ values towards the south (1570 $\mu\text{mol L}^{-1}$) compared to the north (1810 $\mu\text{mol L}^{-1}$). Elevated TCO₂ levels were observed at shallower depths between 13° to 17°N.

The partial pressure of carbon dioxide (pCO₂) (Fig. 6) which indicates interaction between the sea and atmosphere varied between 300 to 450 μatm in the surface layer during the southwest monsoon in the central Bay. During fall intermonsoon, the surface layer showed a maximum concentration of 550 μatm around 7 to 9°N. The western margin showed pCO₂ levels of 550 μatm at 40 m during the southwest monsoon whereas similar levels of pCO₂ were observed upto 10 m at 11°N during fall season. A meridional decrease of pCO₂ towards the north was observed along the western margin as well as offshore waters. Pockets of pCO₂ (450-500 μatm) higher than the atmospheric pCO₂ levels (360 μatm) were observed in the surface layer upto 20 m in the open ocean during the winter season. Eddy at 11°N elevated the water mass from 60 m to 20 m with a concentration of 700 μatm . The western margin also showed marginally higher pCO₂ levels in the surface layer upto 40 m. Evaluation of fluxes of carbon dioxide during the southwest monsoon indicate an average flux of 5.3 $\text{mmol m}^{-2} \text{d}^{-1}$. However, the northern region (18-20°N), which is characterized by strong gradients in salinity, suggests absorption of CO₂ from the atmosphere. During the fall intermonsoon an average flux of 2.0 $\text{mmol m}^{-2} \text{d}^{-1}$ is observed. Changes in physical forcings and moderately higher production result in significantly lower CO₂ flux in this season. The winter monsoon shows the highest average flux of 12.4 $\text{mmol m}^{-2} \text{d}^{-1}$ among the three seasons. Seasonal average fluxes of carbon dioxide are estimated to be 0.64 mol m^{-2} for the southwest monsoon, 0.25 mol m^{-2} for fall intermonsoon and 1.53 mol m^{-2} for the winter monsoon.

Total Organic Carbon (TOC)

Total organic carbon in the surface waters of the open ocean ranged from 140-200 $\mu\text{mol L}^{-1}$ whereas along the western margin it varied from 115 to 190 $\mu\text{mol L}^{-1}$ during the Sw monsoon. TOC in general was higher towards the northern latitudes than the southern latitudes. There was gradual decrease in TOC levels from surface upto 400 m. The depth profiles (Fig.7A) showed accumulation of organic carbon from 400 to 800 m with decreasing trend towards deeper waters. During the non-monsoon seasons the TOC (Fig. 7B &7C) values were in general low in the surface waters perhaps indicating lesser influx of organic matter through the decreased fresh water addition. There were also signatures of accumulation of organic matter in the deeper waters at some stations in the open ocean during these seasons.

Transparent Exopolymer Particles (TEP)

Transparent Exopolymer particles (TEP) showed distinct temporal and spatial variations in the Bay of Bengal (Fig.8). Higher levels of TEP were observed during the southwest monsoon compared to the other two seasons. In the open ocean, maximum concentration of 1500 to 3000 GX eq $\mu\text{g/l}$ in the upper 50 m was observed at 18°N during the southwest monsoon. Along the western margin highest levels of TEP were observed at 15°N . During fall intermonsoon, higher levels of TEP were observed along the western margin compared to the open ocean with the highest concentration at 19°N . TEP levels were the lowest during spring intermonsoon in the open ocean as well as the western margin.

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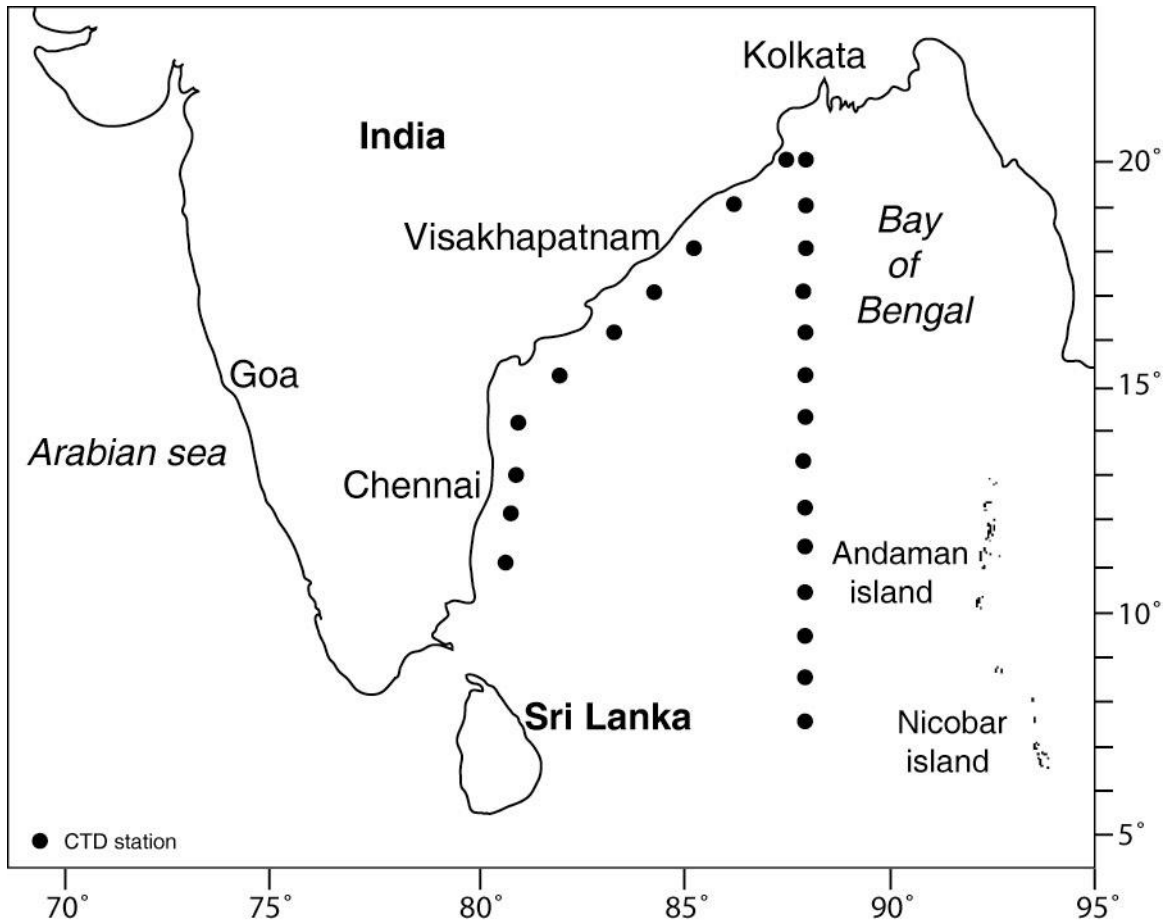


Fig. 1

Fig.1 Map showing the station positions

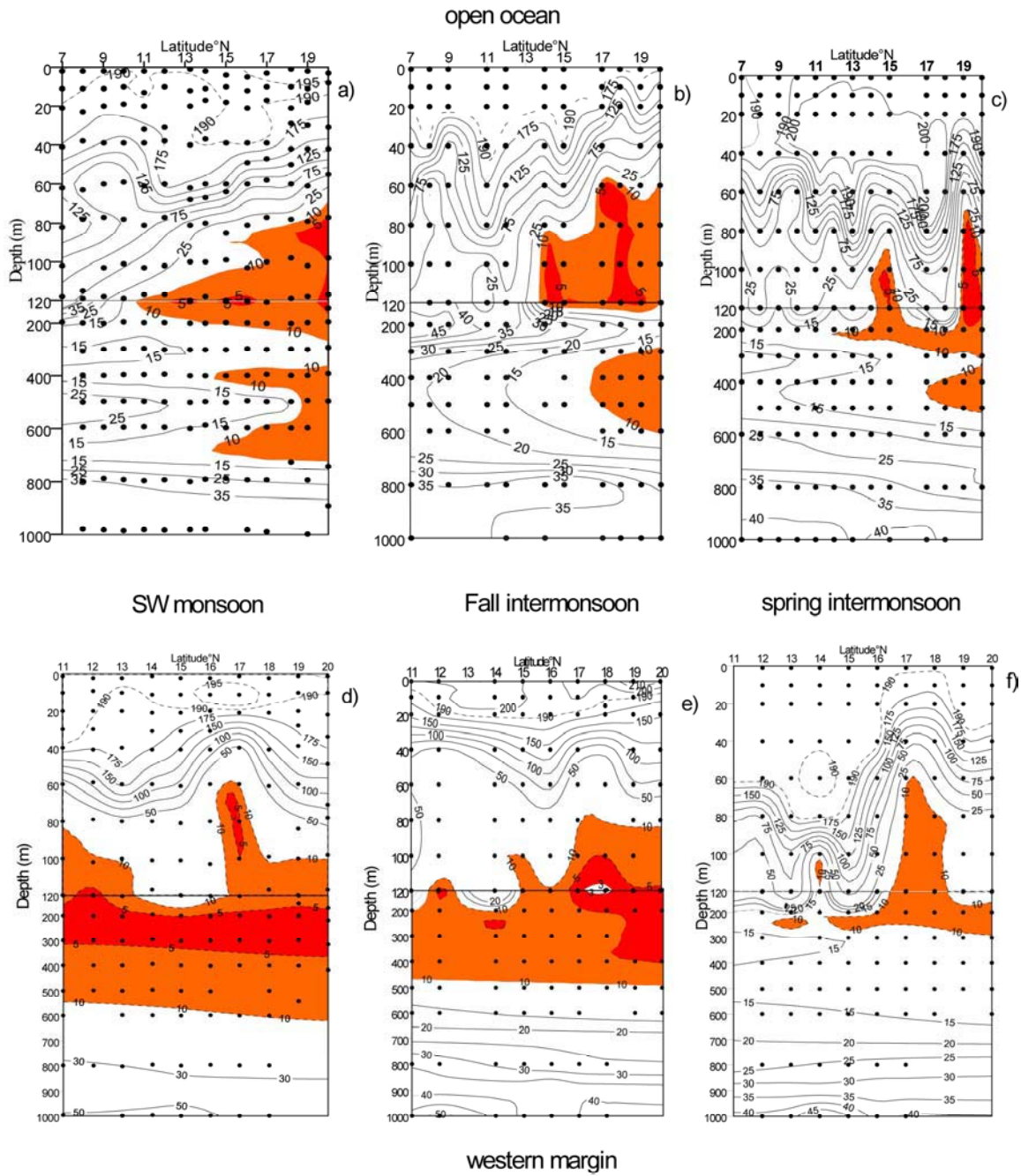


Fig. 2: Distribution of dissolved oxygen during the three seasons

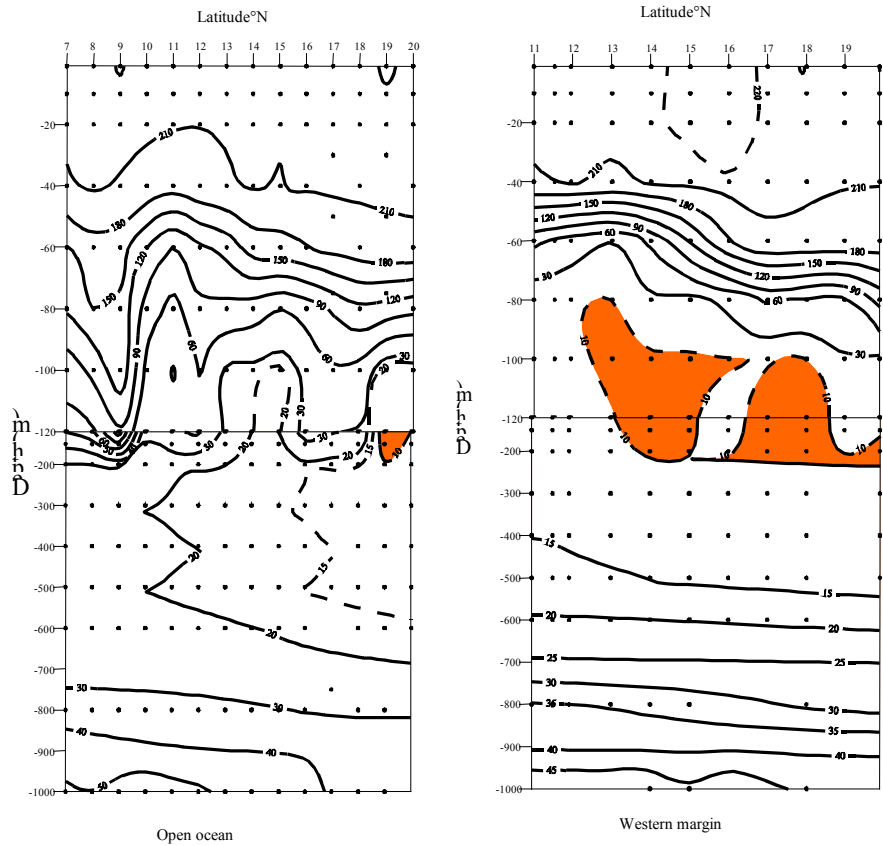


Fig: 3: Distribution of Dissolved Oxygen during

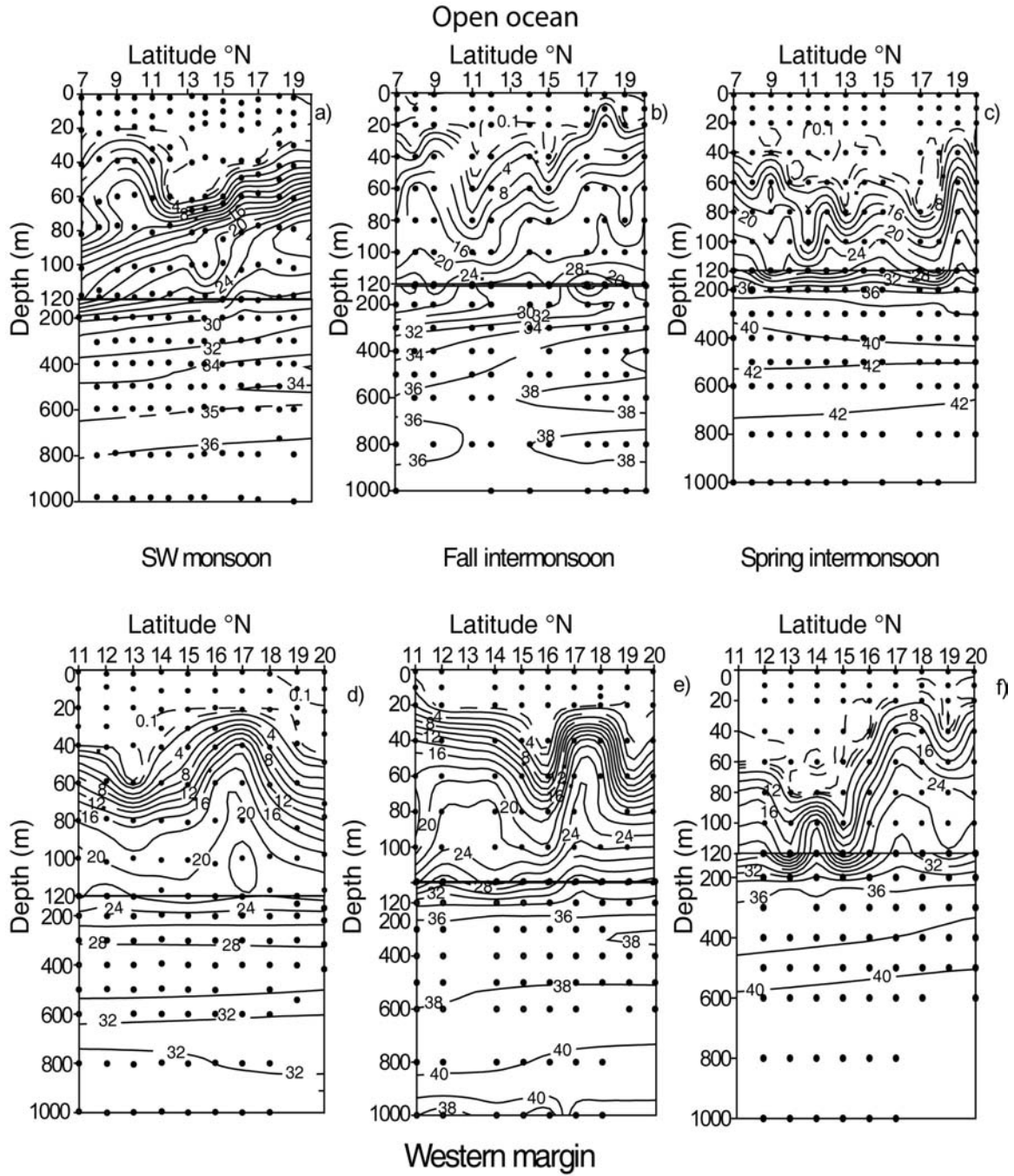


Fig. 4: Distribution of nitrate during the three seasons

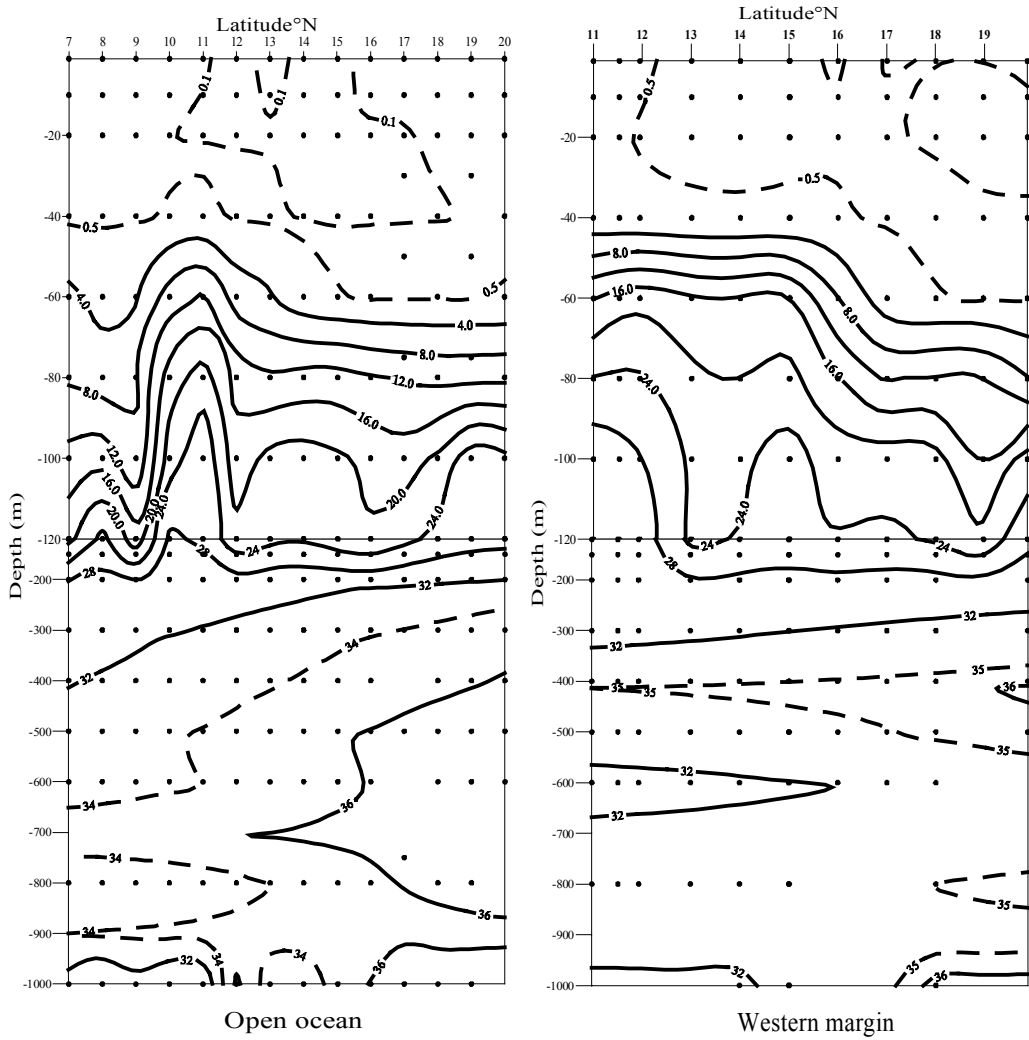


Fig 5: Distribution of nitrate during winter season

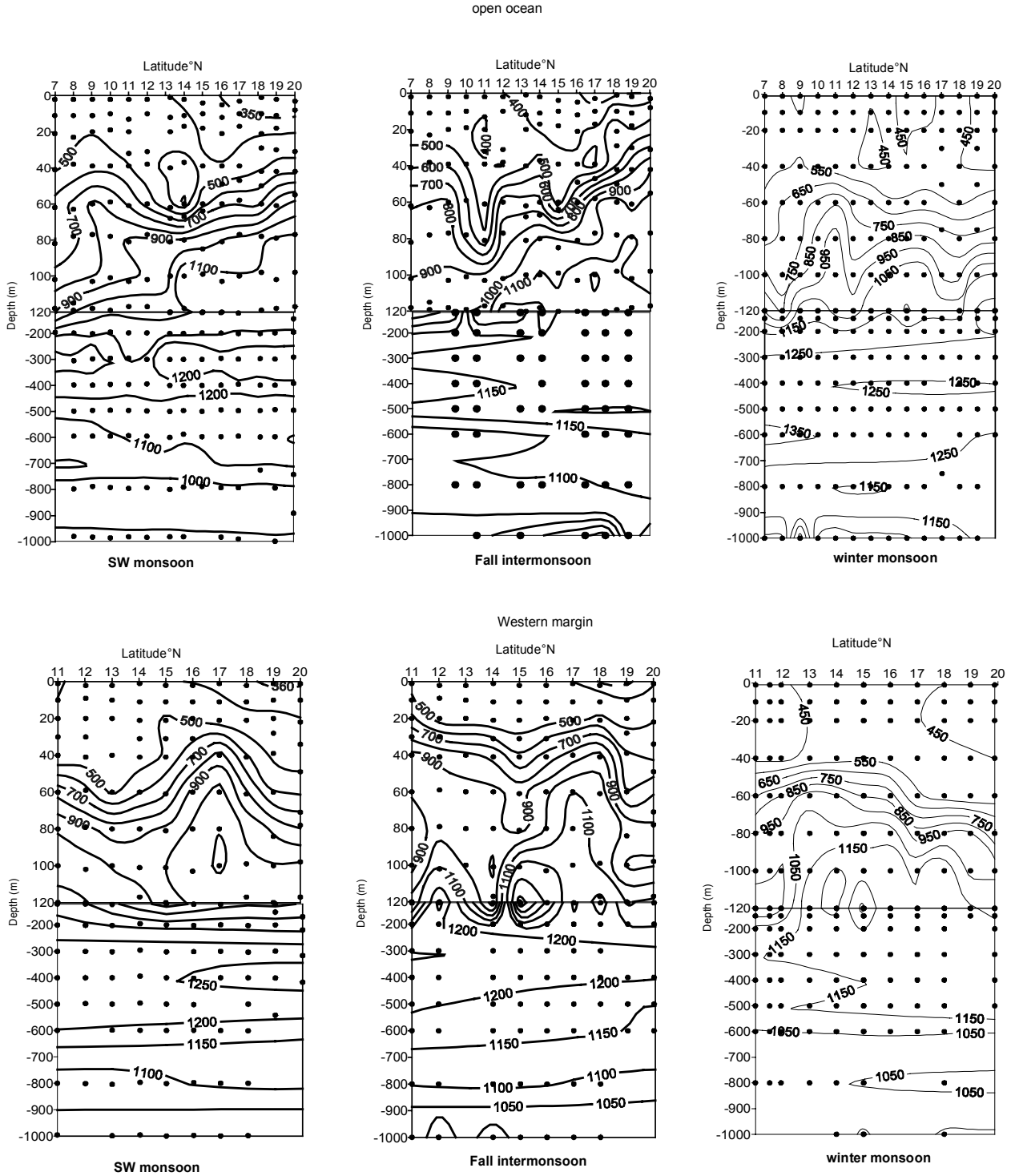
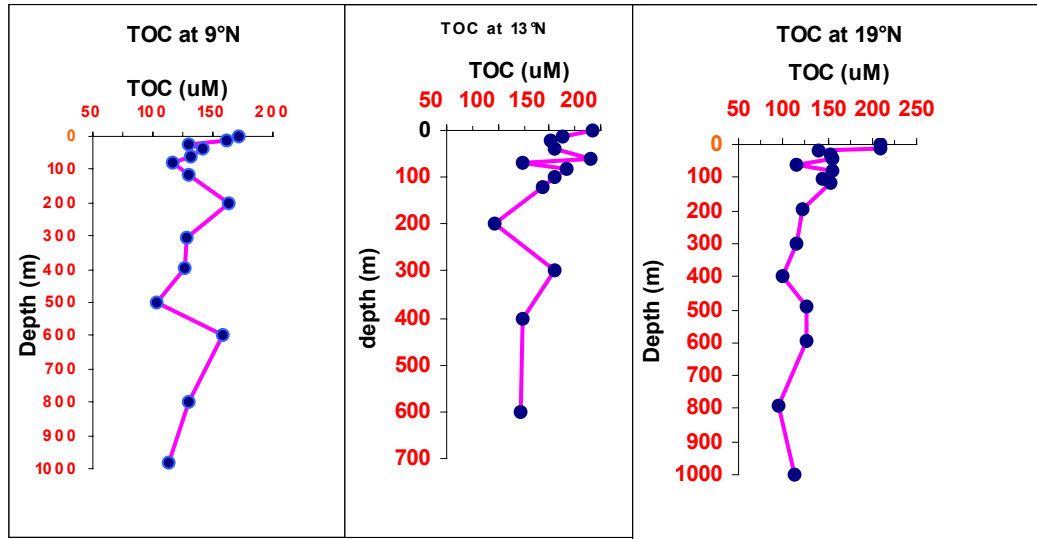
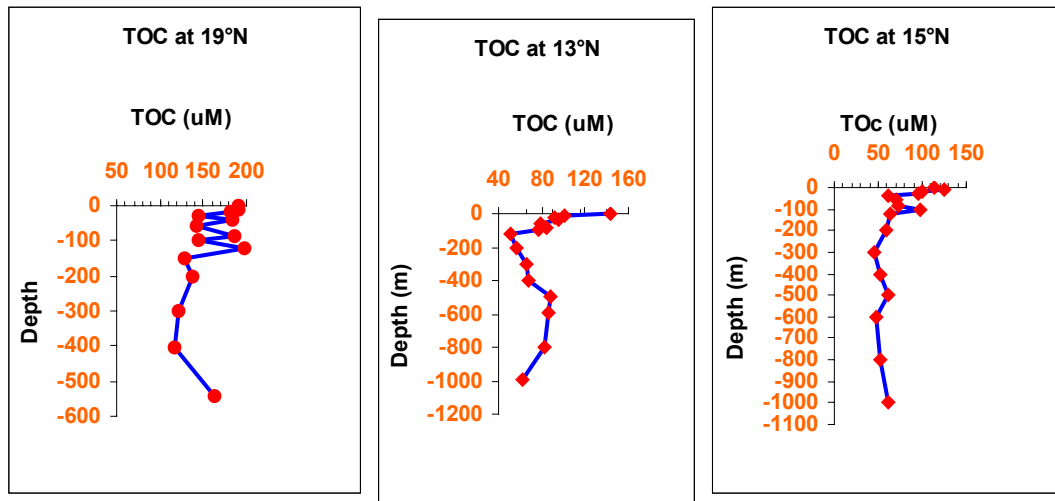


Fig. 6: Distribution of pCO₂ (μatm) in the Bay of Bengal during the three seasons



Open Ocean



Western Margin

Fig.7A : Distribution of TOC ($\mu\text{mol L}^{-1}$) in the Bay of Bengal during SW monsoon

Open ocean

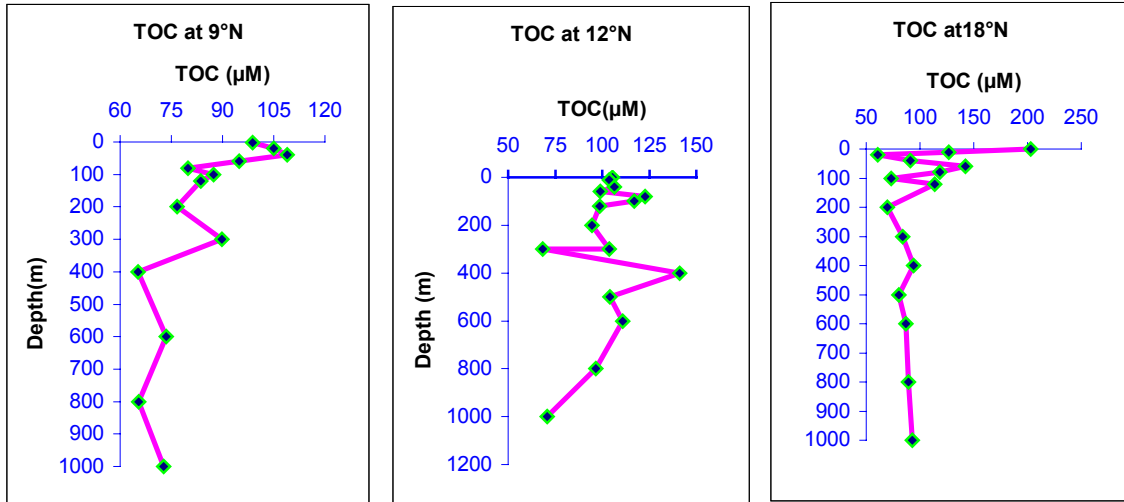


Fig.7B: Distribution of TOC ($\mu\text{mol L}^{-1}$) in the Bay of Bengal during fall intermonsoon

Open ocean

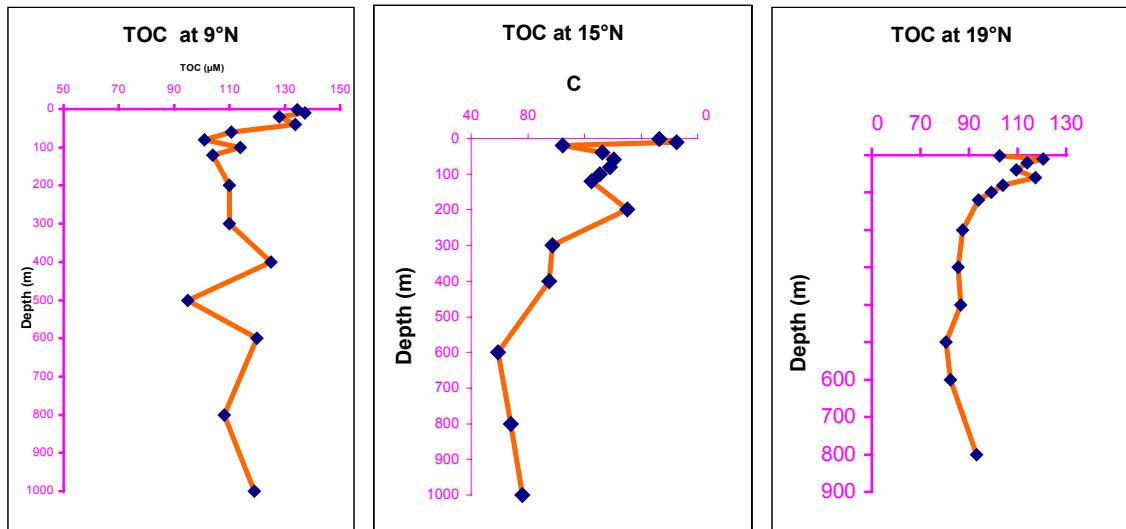
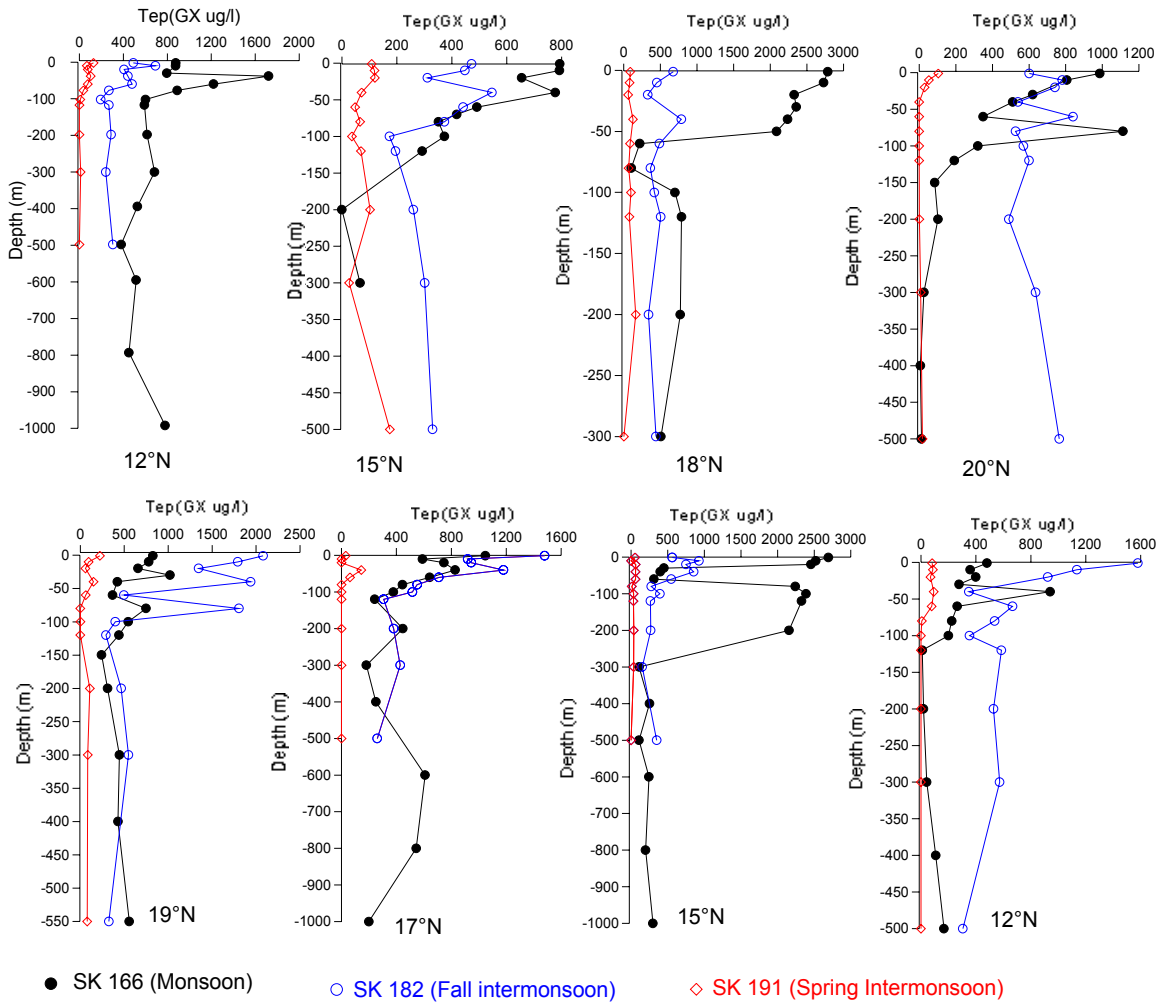


Fig.7C: Distribution of TOC ($\mu\text{mol L}^{-1}$) in the Bay of Bengal during spring intermonsoon

Open Ocean



Western Margin

Fig. 8: Seasonal variability of TEP in the Bay of Bengal

5.2 Biochemical cycling of Carbohydrates, Amino acids and Amino sugars

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Objectives

- (1) To assess the spatial and temporal variation in the carbohydrates, amino acids and amino sugars with reference to biological production and nutrient chemistry.
- (2) To measure the depth related changes in these compounds in order to assess their relative reactivity and diagenetic pathways.
- (3) Identify the sources of organic matter in the Bay of Bengal.
- (4) Define the role of these compounds in the biogeochemical cycling of organic carbon in the water column.

Introduction

Primary photosynthetic production by phytoplankton is the largest source of organic carbon in the ocean. Most of the organic carbon supplied by phytoplankton enters the marine food web via microbial loop, regenerating the nutrients that are recycled in surface waters. The remineralization of organic matter depends on the quality as well as quantity of the organic matter. Carbohydrates and amino acids are the most abundant fractions of the bulk organic matter and they constitute about 40 to 80% in the marine organisms, suspended matter, dissolved organic matter, sedimenting particles and sediments of marine environment (Parsons et al., 1984, Lee & Wakeham, 1987; Cowie & Hedges, 1992). Carbohydrates and amino acids are the most labile fractions of the bulk C and N and they account for a considerable portion of the particulate and dissolved OC and N recycled in both the water and sediments (Lee & Cronin, 1984; Henrich & Farrington, 1987; Burdige & Martens, 1988).

Studies on the distribution of Carbohydrates and amino acids provides useful information on the nature, sources, diagenesis and decomposition of organic carbon and therefore useful biomarkers to study cycling of organic carbon during its transport to the deeper depths (Cowie & Hedges, 1992).

Numerous studies have been carried out in Pacific, Atlantic and Antarctic oceans on the distribution and molecular characterization of carbohydrates and amino acids of suspended particles, sedimenting particles and sediments (Cowie & Hedges, 1992; Benner et al., 1992; Burdige et al., 2000). The amino acids, which are the building blocks of protein, are one of the labile components of the organic matter. The study of amino acids in the marine environments helps to assess the diagenesis and the nature of the organic matter (Lee & Cronin, 1984; Ittekkot et al., 1984b; Muller et al., 1986; Cowie & Hedges, 1992). The abundance of amino acids such as aspartic acid (23.7 mole%) and/or glycine (17.7 mole%) and the aspartic/glycine ratio have been utilized to distinguish inputs from calcareous and diatomaceous materials (Ittekkot et al., 1984b; Muller et al., 1986). The high content of amino acids such as serine, glycine plus threonine and also non-protein amino acids (gamma-aminobutyric acid, beta-alanine and ornithine) (Ittekkot et al, 1984b; Cowie & Hedges, 1992a; Hedges et al, 1994) has been used as good indicators of diagenetic alteration of organic matter.

Another biomarker, amino sugars which are the unusual carbohydrates containing a nitrogen are also the source of organic nitrogen in marine system. The amino sugars are derived from many

sources. Chitin, a polymer of amino sugars N-acetyl-glucosamine (Benner & Kaiser 2003) is produced by many marine organisms. Because of this, it is generally believed that amino sugars are abundant constituents of marine organic matter. They are also important constituents of many biopolymers including polysaccharides, glycoproteins and glycolipids and they are also derived from microbial cell wall components such as peptidoglycan, lipopolysaccharides and pseudopeptidoglycan. Studies carried out in the Pacific and Atlantic Oceans suggest that amino sugars are rapidly utilized as the organic matter sinks to greater depths (Benner & Kaiser 2003).

Carbohydrates are the structural and storage components of both marine and terrestrial organisms. Carbohydrates are also found to play an important role in many environmental processes such as formation of humic substances, removal of dissolved metals, flocculation of dissolved material, production of mucilaginous macroaggregates following eutrophication and in the adhesion of microorganisms. Carbohydrates are the useful biomarkers for determination of source and the diagenetic pathways of organic material in the aquatic environment. The storage sugars are found to be relatively labile and are utilized rapidly by the *in-situ* organisms as compared to the structural sugars. Studies on molecular level analysis of carbohydrates of marine samples have shown that the individual monosaccharides are useful as tracers. For example, the glucose: ribose ratio has been used to distinguish inputs from marine and terrestrial source, ratio >20 indicating the terrestrial source (Degens & Mopper, 1976; Liebezeit, 1986). In the marine environment, the arabinose/ fucose ratio is used to differentiate inputs from calcareous and siliceous material in sediment trap material (Ittekkot et al., 1984). Cowie and Hedges (1984) have suggested the use several monomers and the ratios to assess the inputs from terrestrial, phytoplankton, zooplankton and bacteria. For example, they proposed the use of mannose/ xylose ratio, the total percentage distribution of ribose plus fucose as well as arabinose plus galactose in sugar fraction to distinguish various sources of organic matter. Similarly, the hexose/ pentose ratio has been utilized to identify the inputs from the soil organic matter.

There are numerous studies describing physical, chemical and biological characteristics of the water from the Bay of Bengal (Kumar et al 2002; Madhupratap et al 2003). In contrast, only a few studies have focused their attention on the characterization of organic matter with particular reference to the bulk parameters such as organic carbon, nitrogen, carbohydrates and proteins in the Bay (Bhosle et al 1992; Unger et al 2005). Therefore, little is known about the molecular level characterization, distribution and cycling of organic matter in the Bay of Bengal. The present research aims to study the distribution of carbohydrates, amino acids and amino sugars in particulate matter and sediments and to use these results to define the importance of the carbohydrates, amino acids and amino sugars decomposition in the cycling of organic carbon and nitrogen in the Bay of Bengal.

Parameters measured

1. Suspended particulate matter (SPM)
2. Chlorophyll *a* (Chl *a*)
3. Particulate organic carbon (POC) and Particulate nitrogen (PN)
4. Amino acids
5. Amino sugars
6. Carbohydrates

Material and Methods

During each of the cruises, seawater samples from the same nine stations (5 off shore stations and 4 near shore stations) were sampled from eight discrete depths, using Niskin water samplers (30l) attached to the CTD rosette system. Seawater samples were filtered onto pre-ashed (450° C, 4 hr) GF/F glass filter papers (47 mm, 0.7 µm) for the various parameters.

The filters for Chl *a* were frozen immediately at –20 ° C till further analysis, whereas, the filter papers for other parameters were dried at 50° C in a electrical oven onboard and further stored at –20 ° C till further analysis.

The six sediment cores collected during SK-182 and one core collected during the SK-191 cruise were cut at every 2 cm intervals upto 20 to 30 cm and then dried onboard in the oven at 50° C. In the shore laboratory sediments were powdered and sieved through 355-µm sieves in the laboratory for further analysis.

Bulk parameters

The SPM retained on the pre-ignited and pre-weighed GF/F glass filters was desalted by washing with distilled water, the filter paper was then dried at 50° C in an oven, cooled in dessicator, the filter was then weighed on the micro balance (Mettler Toledo AT20), so as to obtain SPM.

The Chl *a* was extracted with 90 % acetone overnight in dark at 4°C, samples were centrifuged and the clear supernatant analyzed using fluorescence spectrophotometer (Parson et al., 1984).

The SPM samples for POC and PN analysis were pre-treated overnight with the fuming HCl in desiccator, dried at 50 °C. Samples were packed in the aluminum foil and were analyzed using Perkin Elmer, Elemental analyzer 2400 CHN.

Total organic carbon (TOC) in sediment samples was analyzed by TOC analyzer (Schmadzu TOC – 5000A with a quartz combustion, Japan). A known quantity of dried, ground and homogenized sediment sample was placed into a clean carbon free combustion boat and the total carbon (TC) was analyzed at 900° C. Inorganic carbon (IC) was analyzed after acidifying the sediment sample with 0.5 ml of orthophosphoric acid at 200° C. Total organic carbon was obtained by subtracting the IC from the TC.

Organic nitrogen from sediment was determined by the persulfate oxidation method (Smart et al., 1983). In this method nitrogen compounds were converted to nitrate by alkaline persulfate digestion at 115°C in autoclave under pressure and the resultant nitrate-nitrogen was reduced to nitrite –nitrogen by passing the cadmium amalgam column. Finally the nitrite was estimated by diazotisation and coupling with aromatic amines and measured at 543 nm by spectrophotometer.

Amino acid and amino sugars analysis

Amino acid concentrations and composition were determined by reverse phase high performance liquid chromatography (HPLC) (Lindroth and Mopper, 1979; Bhosle, 1993; Bhosle et al., 2005). In brief, samples (Suspended matter and Sediment) were digested in 6 N HCL at 110°C for 22 hrs. After hydrolysis the hydrolysates were neutralized with 6 N NaOH, centrifuged and supernatant collected. An aliquot of the sample is then derivatized with o-phthaldialdehyde

(OPA) and 2-mercaptoethanol reagent and subsequently injected over the 5 μm reversed phase Shim – Pack HRC-ODS C-18 column. A binary solvent system consisting of 50 mM sodium acetate buffer (pH 6.5) containing 3% tetrahydrofuran and methanol to separate the individual amino acids from the amino acid sample mixture and subsequently detected by fluorescence (excitation $\lambda = 328$ nm and emission $\lambda = 450$ nm). Identification was done using the retention time and the concentration was determined by comparing the sample area peak with that of the standards (sigma). The calculation was done with the help of the data handling system installed in the HPLC instrument.

Carbohydrates analysis

Suspended matter and sediment samples were analysed for carbohydrates as described by Bhosle et al (1992). In brief, samples were treated with 12 M Sulfuric acid for 2 h at room temperature, diluted and digested for 3h at 100°C. After hydrolysis the samples were neutralized and concentrated. The liberated monosaccharides were reduced to alditol using sodium borohydride. They were then converted to alditol acetates by treating with pyridine: acetic anhydride (1:1). Alditol acetates were then separated using gas chromatography and further quantified using appropriate standards and the data handling software.

Results and Discussions

Bulk Parameters

Suspended particulate matter (SPM)

SPM varied from 0.2 to 15 mg/l, 0.7 to 11.3 mg/l and 0.3 to 5 mg/l during summer monsoon, fall intermonsoon and spring intermonsoon, respectively. The values recorded here are in the range of 0.05 – 122 mg/l as observed by Rao (1985), but these values are relatively lower compared to other sea and oceans (Telang et al., 1991; Gordeev et al., 1996) The surface concentration of the SPM was higher during the summer monsoon cruise, followed by fall intermonsoon, whereas the concentration of SPM was lowest during spring intermonsoon cruise in both off shore and near shore stations. The Concentration of SPM increased from south to north in the off shore stations. Maximum surface SPM concentration was observed at station 12 and 18, this higher concentration is mainly due to their close proximity to the major rivers, such Ganges-Bhramaputra and Godavari.

Chlorophyll a (Chl a)

The surface Chl *a* concentration varied in the range of 0.024 - 0.177 $\mu\text{g/l}$, 0.009 – 0.039 $\mu\text{g/l}$ and 0.0009 – 0.0074 $\mu\text{g/l}$ during summer monsoon, fall intermonsoon, spring intermonsoon cruises, respectively. The higher values of Chl *a* were observed during summer monsoon in both the off shore and the near shore stations. This high value indicates higher plankton biomass during the summer monsoon another reason could be the higher nutrient contents brought in by the major and the minor rivers, which in turn must have supported the plankton growth. The Chl *a* concentration was lowest during the spring intermonsoon cruise. The Chl *a* concentration was higher in the upper 100 m of the water column. A sub surface Chl *a* maxima between 30m – 60m was observed at most of the stations in the Bay of Bengal.

Particulate organic carbon (POC)

POC values were in the range 29.2 - 178 $\mu\text{g/l}$, 22.4 – 343.1 $\mu\text{g/l}$ and 30 –108 $\mu\text{g/l}$ for the summer monsoon, fall intermonsoon and spring intermonsoon, respectively. The POC values reported here are relatively lower than those reported earlier for the Bay of Bengal (Radhakrishna et al 1978; Bhattathiri et al 1980; Nandakumar et al 1987). The reason for such difference may be due to different analytical methods used for the analysis of POC. Nevertheless, the POC concentrations observed were similar to those reported for other oceanic regions (Gordon et al 1979; Gordon and Cranford 1985). The surface POC concentration during summer monsoon increased from south to north in both off shore stations as well as in the near shore stations. The highest POC concentration was observed at station 12 (132.8 $\mu\text{g/l}$) during the same cruise. The reason for the high POC concentration observed at this northern station may be due to the inputs of terrestrial material from rivers such as Ganges- Bhramaputra and Mahanadi. During the fall and spring intermonsoon cruise the surface concentrations at station 03 was relatively higher, while no particular trend was observed at the other stations. In the near shore stations, during the fall and spring intermonsoon cruise highest POC concentration was observed at Station 16 (85.9 and 81 $\mu\text{g/l}$) and Station 18 (96.5 and 80 $\mu\text{g/l}$). The source for the high POC at these stations is the two rivers Mahanadi and Godavari. The observed spatial variability in the POC in surface samples may be due to differences in the input of autochthonous or allochthonous organic matter at these locations of the Bay. Depth related variations were also observed during these three cruises. The POC concentration was found to be higher in the surface waters as compared to the deeper depths. The POC concentration decreased with the increasing water column depth with some exceptions. This decrease suggests their utilization by the *in-situ* organisms (Gordon and Cranford 1985). During the summer monsoon cruise, at station 9 the distribution of POC did not show much variation through out the water column depth, indicating a balance in the supply and utilization of these compounds. Some stations (03, 06, 12 and 18) during the summer monsoon cruise, showed decrease in POC concentration in the upper 500 m of the water column and then increased again at 1000 m. These concentrations of POC recorded at 1000 m were relatively higher than those measured at the surface of these stations, suggesting the input of organic matter by microbial biomass at these depths. Higher Chl *a* concentration and lower POC/Chl *a* ratio observed indicates that phytoplankton derived organic material was the major source during the summer monsoon and fall intermonsoon, respectively.

Particulate nitrogen (PN)

PN values were in the range 1.6 – 39.8 $\mu\text{g/l}$, 4.8 – 45.9 $\mu\text{g/l}$ and 2.0 –17.3 $\mu\text{g/l}$ for the summer monsoon, fall intermonsoon and spring intermonsoon, respectively. The surface PN concentrations were relatively higher during fall intermonsoon cruise in both off shore and near shore station compared to summer monsoon and spring intermonsoon. This high surface concentration suggests that the organic matter was comparatively richer in nitrogen. Depth related variations were also observed in PN at these stations during three cruises. PN also was found to be higher in the surface waters and it was observed that its concentration decreased with increasing depth with some exceptions. This suggests the presence of fresher organic rich material at surface and its subsequent utilization by the mid water column organisms (Gordon and Cranford 1985). During summer monsoon, like POC, PN concentration at station 9 also did not show any variation with water column depth. Higher PN concentrations were also recorded at 1000m depths at stations (03, 06, 12, 14 and 20) during summer monsoon and station 20 during spring intermonsoon was observed. These concentrations of PN recorded at 1000 m were relatively higher than those recorded at surface waters of these stations, suggesting the input of organic matter by microbial biomass at these depths.

C/N ratio

C/N ratio is a useful tool to assess the nature of organic matter. It has been observed that the fresh and degraded organic matter has low and high C/N ratio, respectively. For example, fresh phytoplankton and bacteria exhibit an average C/N ratio of 7 and 4, respectively (Lee and Furhman, 1987, Nelson and Robertson 1993). This ratio is found to increase with the microbial decomposition of organic matter, since nitrogen is utilized faster than the carbon (Lehmann et al 2002). Similarly, the organic matter derived from terrestrial plants has high (> 24) C/N ratio (Elser et al 2000). Most of the values of the C/N ratio of the SPM sample of the Bay during the summer monsoon and fall intermonsoon were in the range of values recorded for phytoplankton and bacteria. High C/N ratio (> 9) of the surface SPM during summer monsoon at stations 12 and 20 and at all the stations during spring intermonsoon indicates that the organic matter was relatively more degraded. Furthermore, decreases in C/N ratio at 1000 m was also recorded at many of the stations during the summer monsoon and fall intermonsoon cruises indicating the occurrence of relatively fresh organic matter at this depth (Nelson and Robertson 1993). The seasonal and the depthwise changes in the C/N ratio reflects a significant change in the quality of material being produced and /or changes in the relative contributions of autotrophs, heterotrophs, bacteria and detritus.

Amino acid in suspended matter

a. Amino acid concentration

Total hydrolysable amino acids (THAA) concentration ranged from 2.6 - 35.7 µg/l, 4.0 - 62.5 µg/l and 1.8 - 34.5 µg/l during summer monsoon, fall intermonsoon, spring intermonsoon cruises, respectively (Fig 1). These values are in the range of values reported for the other sea and oceans by earlier workers (Siezen and Mague, 1978; Lee et al., 2000; Sheridan et al., 2002). The amino acid concentration was relatively higher during the fall intermonsoon cruise, compared to the other two cruises. The surface THAA concentration did not show any particular trend spatially during the cruises. THAA concentration in the Bay showed positive correlation with Chl *a*. The amino acid concentrations were higher in the surface waters and subsequently concentrations decreased with the increasing water column depth. The presence of *in-situ* organisms in the upper 100 m of the water column may be responsible for the rapid decrease of the amino acids in the upper 100m (Lee et al., 2000; Pantoja et al., 2004). Few stations (03, 06 and 09) in the Bay of Bengal showed increase in THAA at 1000 depth, the reason could be the presence of microbial community and bacterial re-working at the deeper depths.

b. Amino acid carbon and nitrogen percentage

THAA-C account for 2.0 - 27.1%, 7.1 - 27.1% and 2.1 - 19.5 % of POC whereas THAA-N varied from 2.3 - 58.4 %, 4.1 - 53.5 % and 6.4 - 41.5 % in the off shore and the near shore stations, during summer monsoon, fall intermonsoon, spring intermonsoon cruises, respectively (Fig 2 & 3). These values were lower than that observed by other authors for the various seas and oceans (Siezen and Mague, 1978; Muller et al, 1986; Cowie and hedges, 1996; Nguyen and Harvey, 1997; Lee et al., 2000, Unger et al., 2005). THAA-C and THAA-N are the labile components of

the bulk POC and PON. THAA-C and THAA-N are utilized preferentially over the bulk POC and PON, hence they are used as proxies of freshness indicators. In living marine organisms, the THAA-C and THAA-N varied from 30 to 70 % and 50 to 80 %, respectively (Cowie and Hedges, 1994; Cowie et al., 1995). In the present study relatively higher percentage was observed at the surface and this percentage was found to decrease with increasing water column depth, indicating the input of fresher organic matter at the surface. Lower %THAA-C and %THAA-N observed during spring intermonsoon cruise, indicates that the material was relatively poor in fresh biogenic material or has undergone substantial degradation and/or dilution by inorganic or amino acid poor soil material. This was evident from the inverse trends observed between THAA and SPM.

c. Amino acid monomeric composition

The average mole % composition of individual amino acids for the three cruises is shown in Fig4. The 16 individual amino acid components were identified by HPLC of which two acidic, two basic, nine neutral and three were non-protein amino acids. Since glycine and threonine could not be separated on the column used for the separation of amino acids and hence expressed as glycine plus threonine. Glycine plus threonine were the most abundant and accounted for 17 – 23 %. The other dominant amino acids in the samples were glutamic acid, aspartic acid, serine, leucine, and lysine. It was observed that the amino acids glycine plus threonine and serine generally increased with the water column depth. These three amino acids are closely associated with the biogenic silica in the diatom cell wall and frustules, and are protected from the degradation (Heckly et al., 1973; Cowie and Hedges, 1996). Another reason for their increase in the water column may be their low nutritional value and/ or their synthesis by the organisms. The intracellular amino acids such as aspartic acid, glutamic acid, alanine, valine, isoleucine, leucine, lysine, arginine and phenylalanine generally decreased with the increasing water depth. The decrease of these amino acids with the water column depth indicates their utilization by the *in-situ* organisms during the transport of organic matter through the water column.

The non-protein amino acids such as β -alanine (β -ALA), γ -amino butyric acid (γ -ABA) and ornithine (ORN) were also observed in the samples. These non-protein amino acids are the sensitive indicators of decompositional state of organic matter. β -ALA and γ -ABA are the bacterial decarboxylation products of aspartic acid (ASP) and glutamic acid (GLUT), respectively and ORN degradation product of arginine (ARG). In living organisms the non-protein amino acids are found to be less than 3 % (Cowie and Hedges, 1994). The appearance of non-protein amino acids in the water samples indicates, the decomposition of organic matter (Chase et al., 2003). Non-protein amino acid mole % increased with the water column depth. The ratios of ASP/ β -ALA and GLUT/ γ -ABA were higher at the surface and decreased with the increasing water column depths. From the vertical profile of protein/ non- protein amino acids it is evident that during fall intermonsoon cruise the stations sampled were relatively fresher throughout the water column.

Amino sugars in suspended matter

The Amino sugar concentration in the suspended matter varied from 0.4 – 17.5 nmol/l, 0.02 – 2.31 nmol/l and 0.01 – 2.00 nmol/l during summer monsoon, fall intermonsoon, spring intermonsoon cruises, respectively. The amino sugars concentrations varied in relation with the stations and depth (Fig 5). The amino sugar concentration observed during summer monsoon cruise were higher, whereas the amino sugar concentrations during the fall intermonsoon and

spring intermonsoon are well within the range of values reported for other seas and oceans of the world. For example, Benner and Kaiser (2003) reported large variations (0.18 to 1.7 nmole/l) in total hydrolysable amino sugars of the SPM samples collected from various depths of the Pacific Ocean. The AS accounted for 0.01 - 0.71 %, 0.01 - 0.21 % and 0.01 - 0.27 % of organic carbon and 0.05 - 2.37 %, 0.01 - 0.19 % and 0.01 - 0.83 % of organic nitrogen in the Bay of Bengal during summer monsoon, fall intermonsoon, spring intermonsoon cruises, respectively (Fig 6, 7). These values are in the range of (0.1 to 1.5 % of organic carbon) reported for plankton and the suspended particulate matter collected from the Pacific Ocean (Benner and Kaiser 2003). During the summer monsoon cruise rapid decrease in the concentrations and the % AS-C/OC and AS-N/ON with increasing depth were observed implying that these compounds were rapidly recycled in the upper ocean.

The GLU-N/GAL-N ratio is a useful parameter to differentiate the relative inputs of the organic matter derived from zooplankton and microorganisms in marine waters (Muller et al 1986, Haake et al 1993, Benner and Kaiser 2003). This approach is based on the fact that that GLU-N content is very high in zooplankton, whereas it is relatively low in microorganisms. During the summer monsoon cruise our samples were relatively rich in GAL-N compared to GLU-N. As a result our GLU-N/GAL-N ratios are lower (0.04 to 1.4) than those (1 to 2.5) reported by Benner and Kaiser (2003) for the SPM samples collected from the Pacific Ocean. These recorded ratios are in the range of values obtained for the SPM of Kara Sea (0.63 to 8.69) for phototrophic algae and heterotrophic bacteria. The GLU-N/GAL-N ratio for the SPM of the Bay of Bengal samples is < 2 thereby suggesting that the organic matter was mostly derived from heterotrophic microorganisms.

Carbohydrates in suspended matter

Total neutral carbohydrates (TNCHO) concentrations ranged from 3.5 - 36.0 $\mu\text{g/l}$, 0.86 - 39.0 $\mu\text{g/l}$ and 0.38 - 21.2 $\mu\text{g/l}$ during summer monsoon, fall intermonsoon, spring intermonsoon cruises, respectively (Fig 8). The TNCHO concentrations were higher during the summer monsoon period in both off shore and near shore stations. TCHO concentrations were higher in the surface waters and it decreased with increasing water column depth, indicating their utilization by the *in-situ* organisms.

The TNCHO -C contributed about 1.4 - 25.5 %, 0.5 - 16.2 % and 0.3 - 9.9 % to total POC during summer monsoon, fall intermonsoon, spring intermonsoon cruises, respectively (Fig 9). The contribution of the total carbohydrate -C to the organic carbon is a useful tool for evaluating the degradation state of an organic matter. The higher surface THCHO -C% indicates the freshness of the organic matter. Whereas, the decreasing percentages with the depth indicates the presence of less fresh organic matter in the deeper waters. In the spring intermonsoon samples, the TNCHO -C % was found to be lower, indicating that during this cruise the organic matter was substantially more degraded compared to the other two cruises. During the summer monsoon, fall intermonsoon and spring intermonsoon cruises carbohydrates showed a positive relation with chlorophyll *a* ($r = 0.42 - 0.46$, $P < 0.001$, $n = 66$) indicating phytoplankton to be the source of organic matter, the carbohydrate also showed a positive relationship with POC ($r = 0.58 - 0.60$, $P < 0.001$, $n = 66$).

Monosaccharide composition in suspended matter

The molecular level analysis of carbohydrate samples yielded 8 individual sugars, namely rhamnose, fucose, ribose, arabinose, xylose, mannose, galactose and glucose, in the suspended matter during the three cruises (Fig 10). These sugars occur in the various marine suspended matter samples and contribution of the individual sugars to the total carbohydrates varies according to source and nature of suspended matter.

Of the eight sugars, glucose the most abundant constituent of organic matter was detected during these 3 cruises. Glucose contributed about average 45.3 – 65.5 %, 51.7 – 67.9 % and 48.3 – 72.3 % during summer monsoon, fall intermonsoon, spring intermonsoon cruises, respectively. This contribution is well within the range reported by other authors for suspended matter (Ittekkot et al., 1982; Bhosle et al., 1990). During the summer monsoon cruise it was observed that the average glucose weight % increased with the water column depth, whereas weight % of the remaining sugars showed a opposite trend to that of glucose. The increase of glucose weight % with depth indicates that glucose was not utilized as a nutrient source during this cruise. During the fall intermonsoon and spring intermonsoon it was observed that the glucose content decreased up to 60m depth, indicating its utilization by the *in – situ* organisms. Whereas an increase in galactose, mannose and fucose for the same depths was observed. These monosaccharides are the major components of diatom cell wall (Hecky et al., 1973). It has been observed that the cell wall polysaccharides, decomposes less rapidly than the glucose rich polysaccharides in the ocean (Ittekkot et al., 1982). This indicates the relative stability of the cell wall sugars during the initial period of decompositions.

Several relationships between the sugars have been utilized to study the source and digenic state of the organic matter in the ocean. For example, in our samples, there was significant inverse relationship between glucose and deoxy sugars (rhamnose plus fucose) during summer monsoon ($r = 0.3219$, $P < 0.01$), fall intermonsoon ($r = 0.4621$, $P < 0.001$) and spring intermonsoon ($r = 0.6115$, $P < 0.001$) suggesting the selective utilization of glucose relative to the deoxy sugars. The abundance deoxy sugars relative to glucose indicate degradative state of organic matter (Hedges et al., 1994). Microbial biomass contains high % of deoxy sugars, whereas, the terrestrial input is enriched in arabinose and xylose. In order to determine the presence of alternate carbohydrate source of the organic matter in the bay, rhamnose plus fucose was plotted against arabinose plus xylose on glucose free weight % basis. Inverse relationships were recorded for these two parameters during summer monsoon ($r = 0.4721$, $P < 0.001$), fall intermonsoon ($r = 0.4882$, $P < 0.001$) and spring intermonsoon ($r = 0.4452$, $P < 0.001$) suggesting influence of terrestrial plant material in our samples.

Amino acid, amino sugars and carbohydrates in sediments

Amino acids in sediments

The amino acid concentration in the seven sediment cores collected from the Bay of Bengal varied in the range from 369.7 – 1713.5 $\mu\text{g/g}$. The amino acids concentration in surface sediment was higher for northern stations (14, 16, 17 and 18a). The amino acid concentration was found to be higher in the surface sediment that decreased with sediment core depth (Fig 11). The decrease in amino acid concentration with depth in the sediment core has been frequently reported in the literature. These decreases are generally due to decomposition by benthic macro-and microorganisms (Burdige and Martens, 1988). At station 17, 18 and 24 the amino acid concentration did not show much variation with the depth.

The THAA-C % and THAA- N% varied in the range 0.5 – 4.5 % and 3.1 – 28.5 %, respectively. The depth profiles of percentages of THAA-C and THAA- N were similar to that of the THAA in the sediment. The higher surface percentages indicate the presence of fresher organic matter at the sediment surface (Fig 12).

The C/N ratio varied from 11.5 – 37.3 in our sediment samples. Amino acid composition in the Bay of Bengal sediments measured here followed similar pattern as shown by the previous studies (Dauwe and Middelburg, 1998). The relative concentration of glycine increased with the sediment depth. Previous reports have also shown that mol % of glycine increases with water column depth in suspended particulate matter, in sinking particles, and with depth in sediments (Siezen and Mague, 1978; Lee and Cronin, 1984; Burdige and Martens, 1988). The silica frustules of diatoms are enriched in glycine, threonine and serine (Hecky et al., 1973), and this association provides these compounds protection from microbial degradation in the water column and in sediments (Ingalls et al., 2003). Another reason for their enrichment could be their low nutritional value to benthic organisms and/or its synthesis by the organisms (Fig 13).

It was also observed that the relative proportion of arginine and lysine also increased slightly with increasing depth in our samples. Since basic amino acids strongly associate with the mineral phases in sediments, this has been found to protect them from microbial degradation (Keil and Hedges, 1999).

The non-protein amino acids such as β -alanine (β -ala), γ -amino butyric acid (γ -aba) and Ornithine (orn) were also observed in the samples. The non-protein amino acid concentrations increased with the sediment depth, and it appears that these non- protein amino acids tend to accumulate in the older sediments. The non-protein amino acids are the useful proxies to assess the degradation of organic matter, as β -alanine, γ -amino butyric acid and Ornithine are the microbial degradational products of aspartic acid, glutamic acid and arginine, respectively.

Amino sugars in sediments

The two amino sugars, glucosamine and galactosamine were also abundant in all the sediment samples collected in the Bay of Bengal. The concentration of the two amino sugars ranged from 7.0 – 207.5 $\mu\text{g/g}$ in the sediments of the Bay of Bengal (Fig 14). The sediment samples of station 17 showed higher amino sugar concentration throughout the sediment core depth, also an increase in the concentrations of amino sugars at some depths of station 18a was also observed. The THAS-C% and THAS-N% varied in the range 0.01 – 0.37% and 0.03 – 1.57 5%. The THAS –C and THAS-N did not vary significantly throughout the sediment depth (Fig 15). This is attributed to incorporation of amino sugars in structural biopolymers, such as bacterial cell walls and chitin (Ternay, 1976), which render these amino sugars relatively resistant to decay.

The ratio of glucosamine / galactosamine is a useful tool to differentiate the source of the organic matter in the ocean. It has been observed that glucosamine is an abundant polymer in chitinous zooplanktons, while the galactosamine is relatively more abundant in the microbial biomass. The amino sugar ratio in our samples varied from 0.50 – 4.89, except for some depths the ratio was generally > 2 indicating that the chitinous material from zooplankton was the major source of organic matter in the sediment of the Bay of Bengal.

Carbohydrates in sediments

The seven surface sediment samples from the Bay of Bengal were analyzed for carbohydrates. The carbohydrates in the surface sediment samples ranged from 0.87 – 1.62 mg/g. The carbohydrate concentration varied spatially (Fig 16). The concentration of the carbohydrate was higher in the surface sediments of the northern stations whereas, the concentration decreased towards the southern stations. The carbohydrates carbon contributed about 2.3 – 5.9 % to the organic carbon.

Monosaccharide composition

The sugars rhamnose, fucose, ribose, arabinose, xylose, mannose, galactose and glucose were detected in the surface sediments of the Bay of Bengal (Fig 17). The molecular level analysis showed that galactose, glucose and mannose were the most abundant sugar followed by the arabinose, xylose and Rhamnose at most of the stations (14,16 17, 18 a, 18 and 24) except for station 20, which had high concentration of glucose, followed by galactose and mannose. At station 18a arabinose was the second most abundant sugar, followed by mannose and glucose. The contributions from the other sugars were comparatively low. The difference observed in the carbohydrates is mainly due to the variation in the organic matter sources and decomposition pattern. Abundance of Galactose as a major neutral sugar has also been observed in the NW Mediterranean Sea (Kerherve' et al., 2002) and Black Sea (Mopper, 1977). The source for the galactose has been attributed to phytoplanktonic detritus (Kerherve' et al., 2002). The two hexoses, galactose and glucose are abundant as a cellular storage material (β -glucan and galactan polymers) of both vascular plants and phytoplankton (Cowie and Hedges, 1984). The presence of galactose and glucose accompanied by the mannose, xylose and arabinose at most of the stations analysed indicates that beside phytoplankton, terrestrial plants material also contributed to the organic matter in the analysed sediment samples, since xylose and arabinose are abundant in lignin tissues as arabinoxylan and arabinoglucoronoxylanin the terrestrial plants, whereas, mannose is present as glucoromannan in diatoms and glucomannan in terrestrial plants. This observation was further supported by the presence of these stations close to the river mouths. Many authors have reported abundance of glucose in the sediment (Cowie and Hedges, 1984; Hernes et al., 1996; Campiano and Romano 1988; Jensen et al 2005). Glucose is the most abundant neutral monosaccharide among terrestrial and marine organisms, since its polymerization produces structural or storage compounds as cellulose and β -glucans, respectively. Since the insitu organisms readily utilize glucose the presence glucose signature in the surface sediment of station 20 indicates input of fresh organic material.

Summary

The biomarkers amino acids, amino sugars and carbohydrates were found to be the important constituents of the suspended particulate matter and the sediments of the Bay of Bengal during the summer monsoon, fall intermonsoon and spring intermonsoon cruises. Rapid decrease of the amino acids, amino sugars and carbohydrates and their contribution to organic carbon clearly suggested that these compounds were rapidly mineralized in the water column. The cell wall amino acids such as glycine plus threonine and serine were found to accumulate at the greater depths indicating their refractive nature in both SPM and sediments. The amino sugar, galactosamine was found to be abundant in the SPM of the Bay indicating the contribution from bacteria, whereas, glucosamine from the zooplanktons was found to abundant in the sediments of

the Bay suggesting different source of organic matter input. The monosaccharide glucose was the abundant constituent in the SPM and its concentration increased with water column depth, whereas, galactose followed by glucose was found to be abundant monomers in the sediments of the Bay of Bengal. The study carried over a period of four years indicates that the organic matter showed strong spatial and temporal variations.

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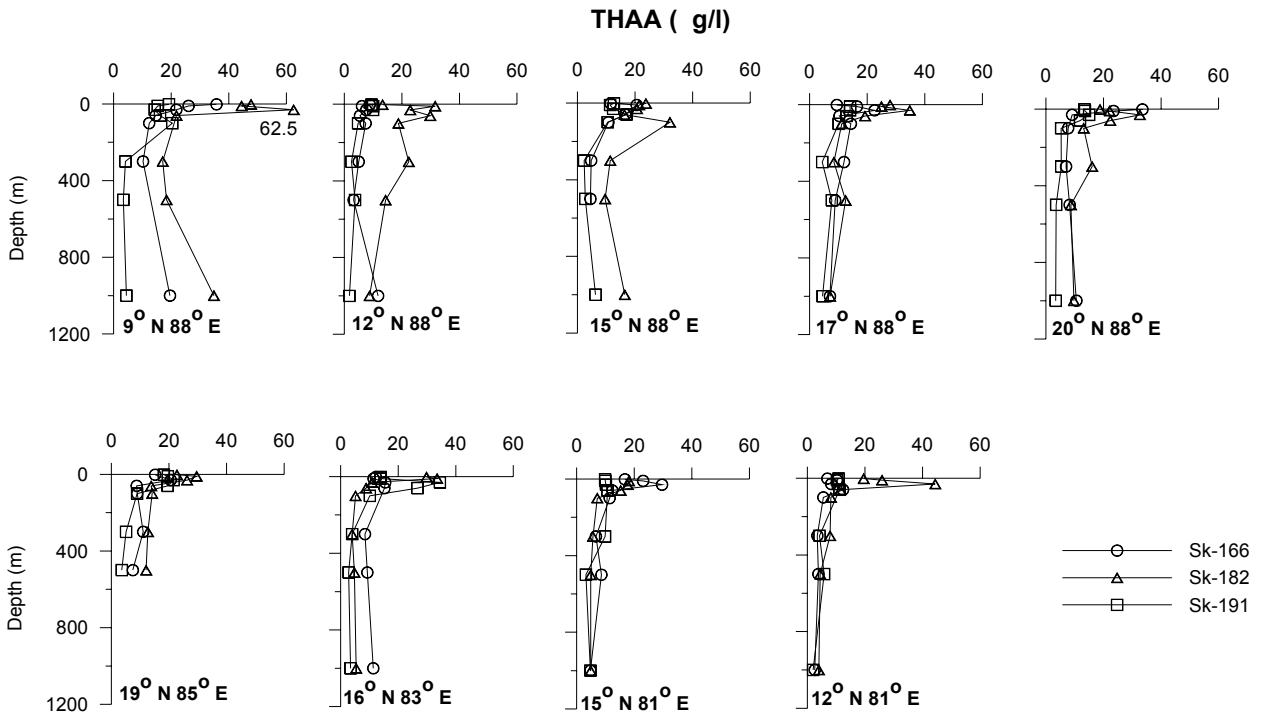


Fig. 1. Amino acid distribution in the SPM of the Bay of Bengal.

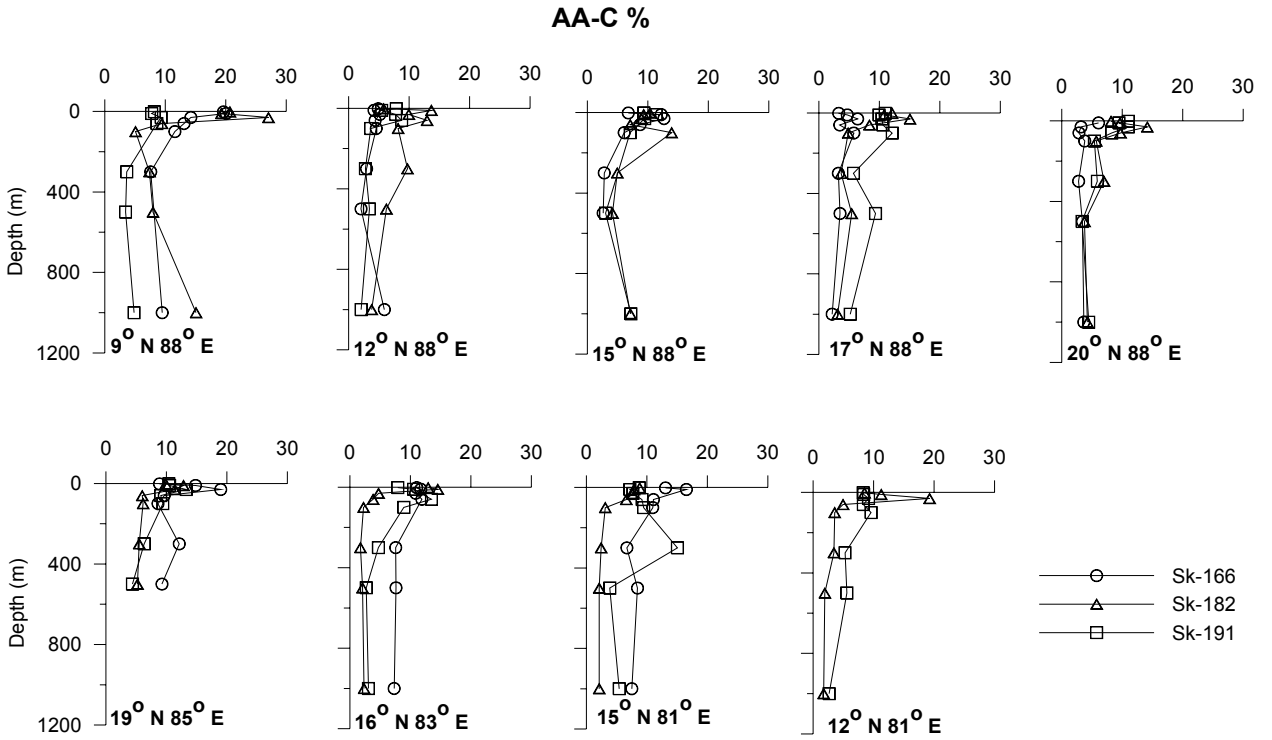


Fig. 2. Amino acid - carbon percentages in the SPM of the Bay of Bengal.

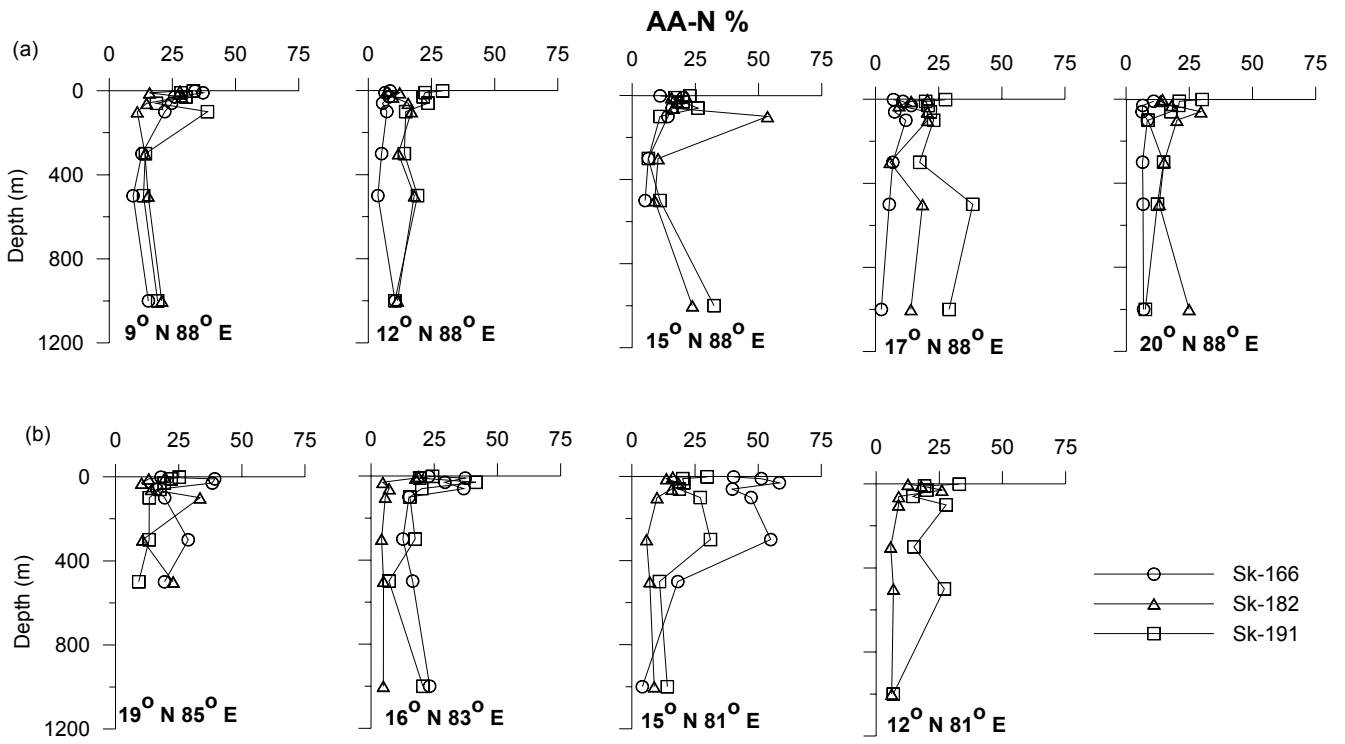
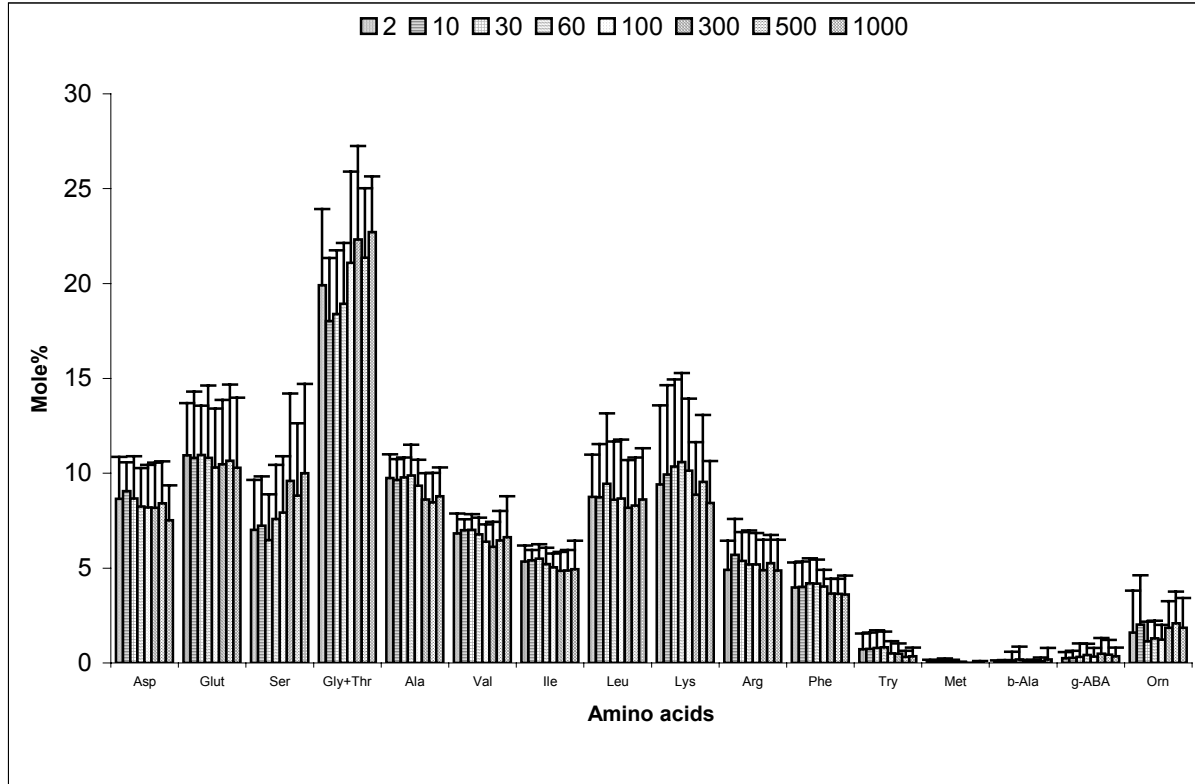


Fig. 4: Average variation in the amino acid composition in the GPM of the Bay of Bengal



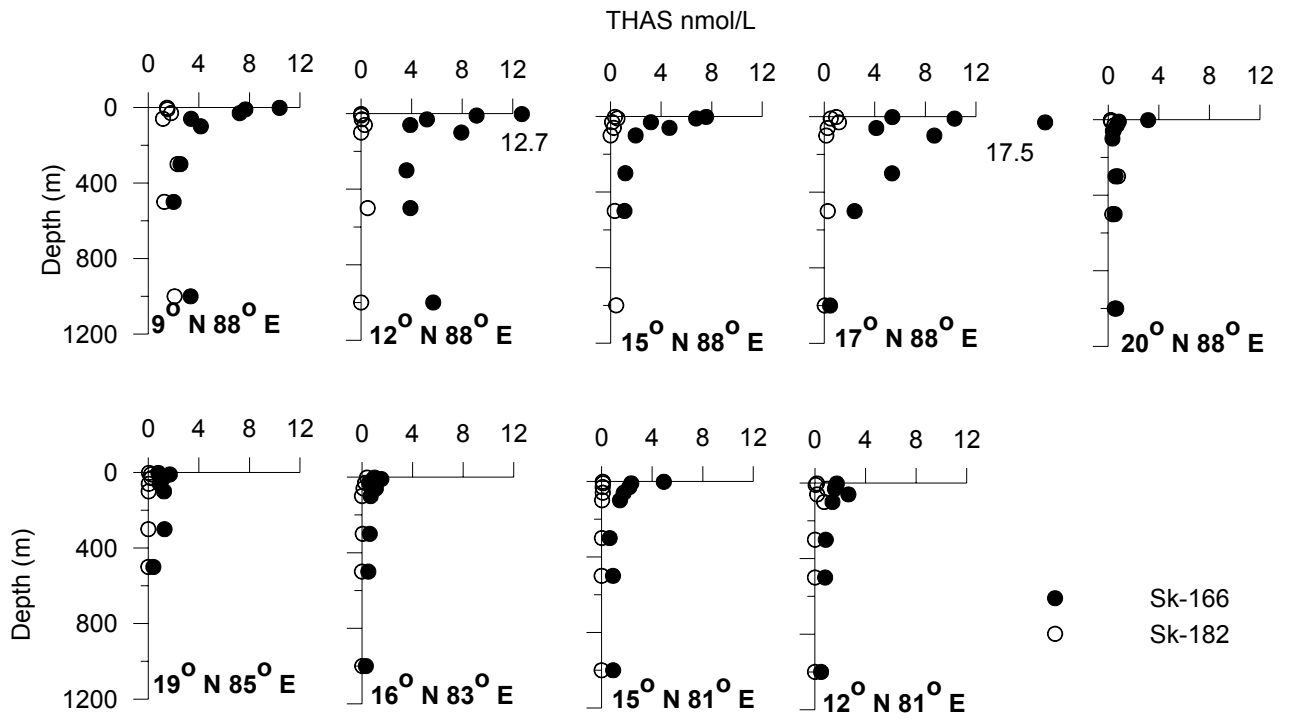


Fig:5. Amino sugar concentration (nmol/L) in the SPM of the Bay of Bengal

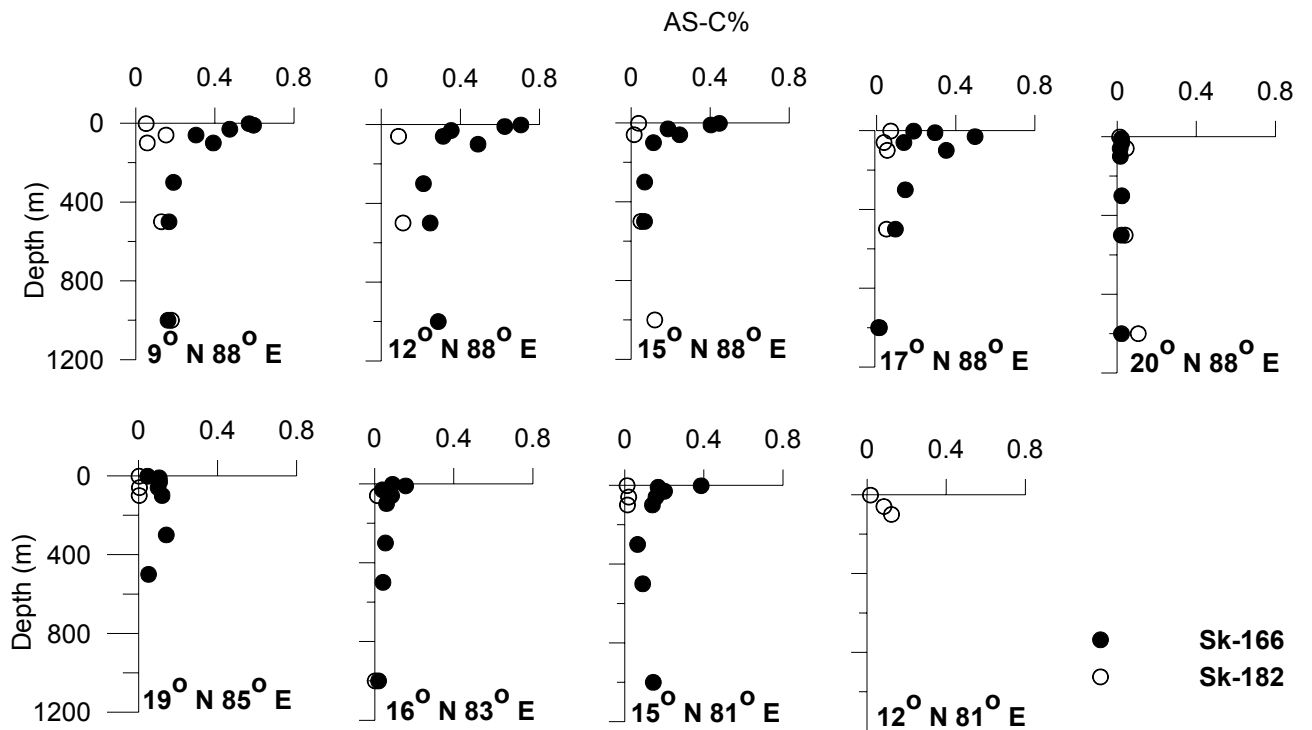


Fig: 6. Amino sugar- carbon % in the SPM of the Bay of Bengal

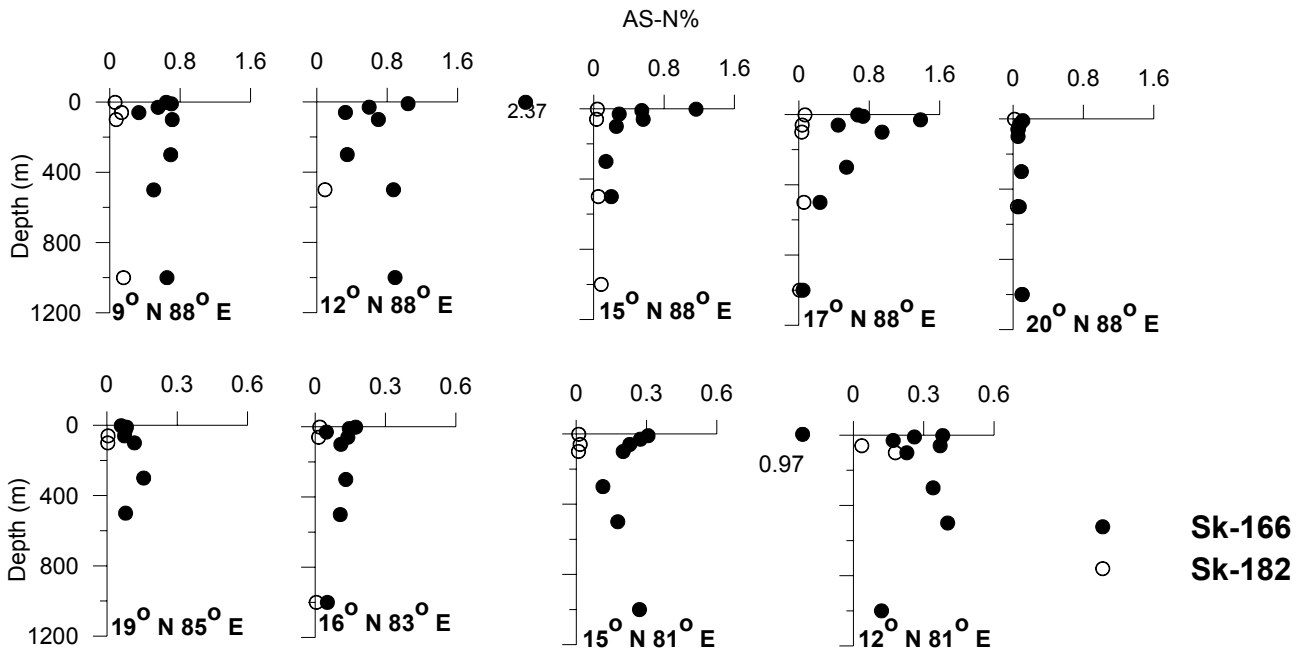


Fig. 7. Amino sugar-nitrogen % in the SPM of the Bay of Bengal

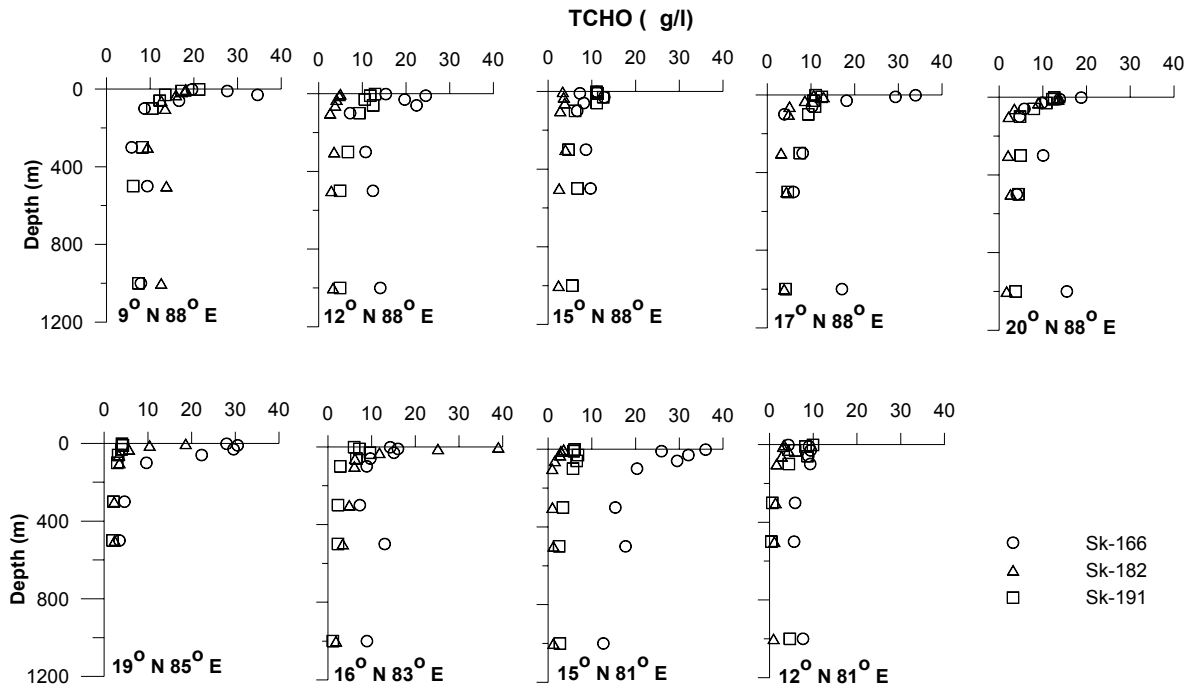


Fig. 8. Verticle profile of cabohydrate concentrations in the SPM samples of the Bay of Bengal

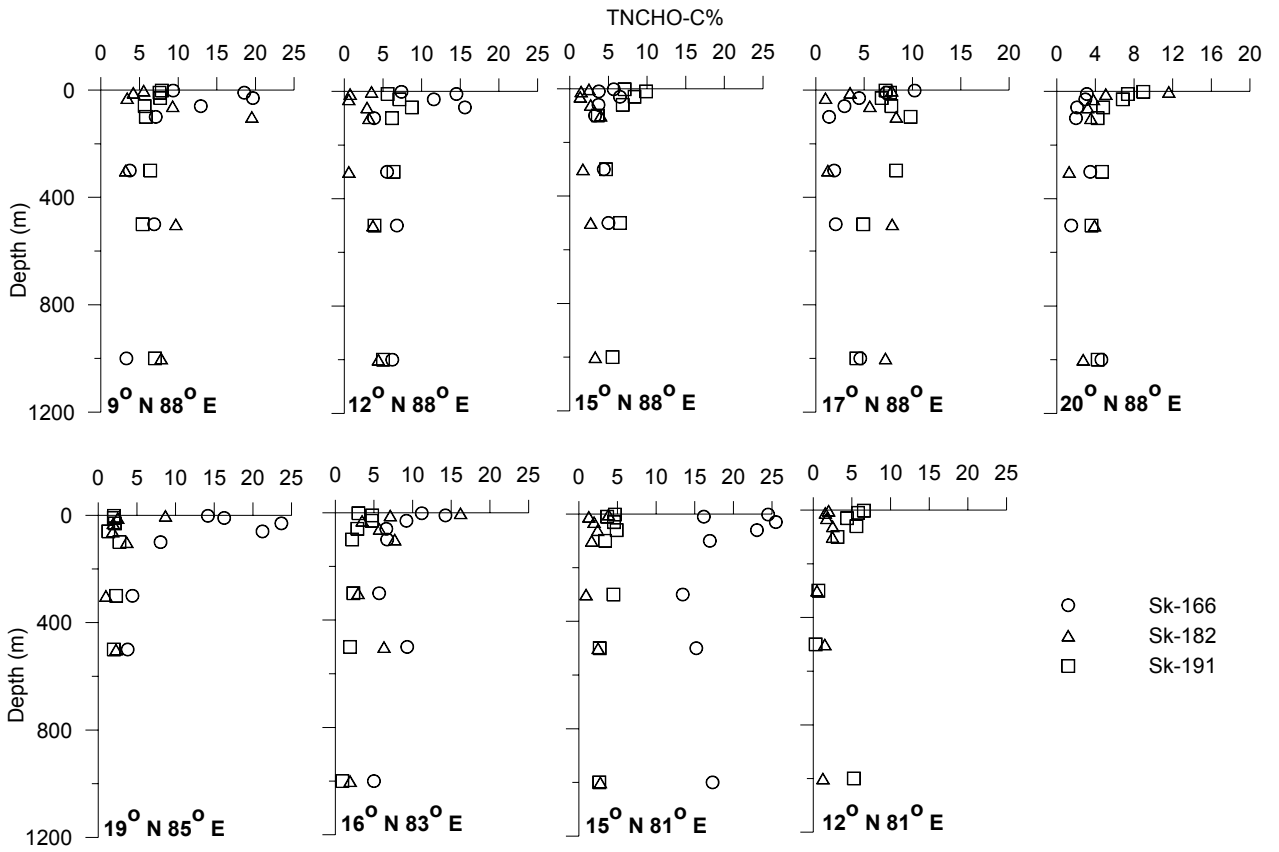
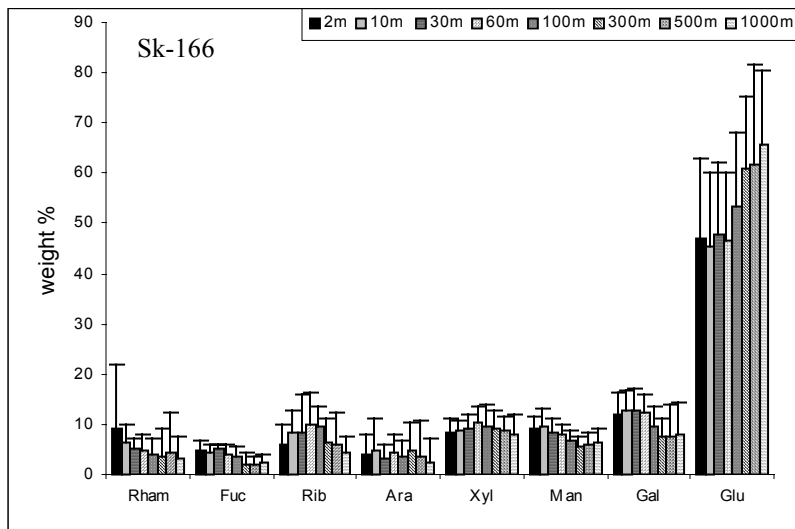


Fig: 9. Vertical profile of carbohydrate- carbon percentages in the SPM of the Bay of Bengal



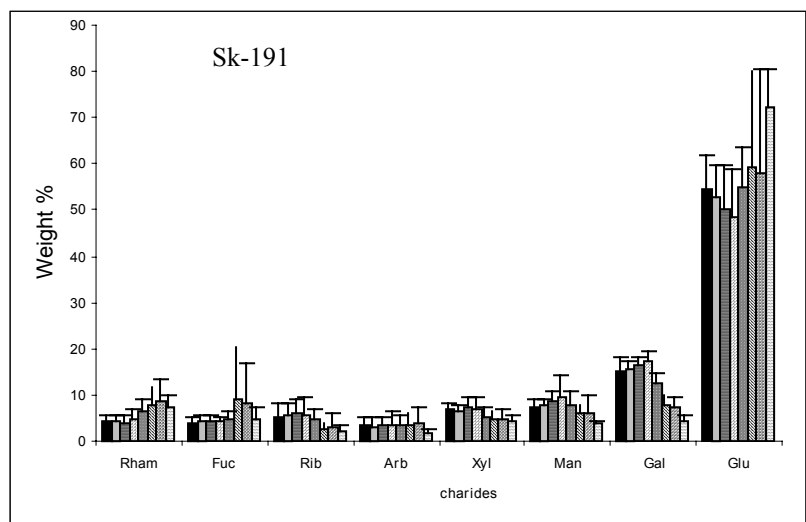
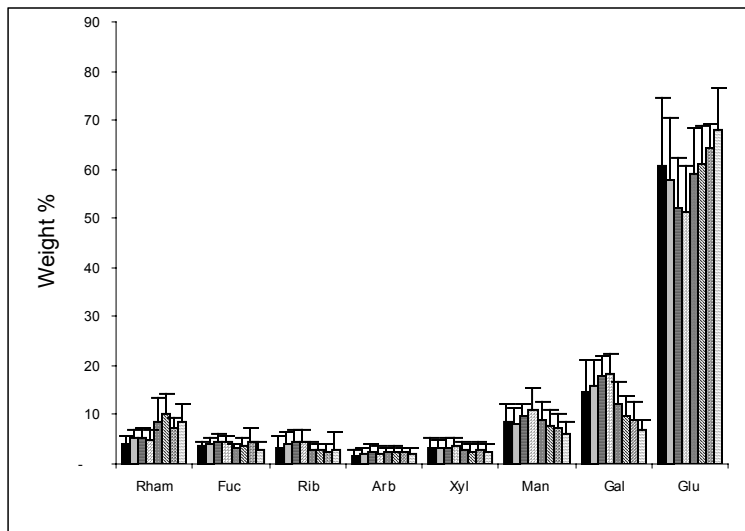


Fig: 10. Variation in the monosaccharide composition in the SPM of the Bay of Bengal

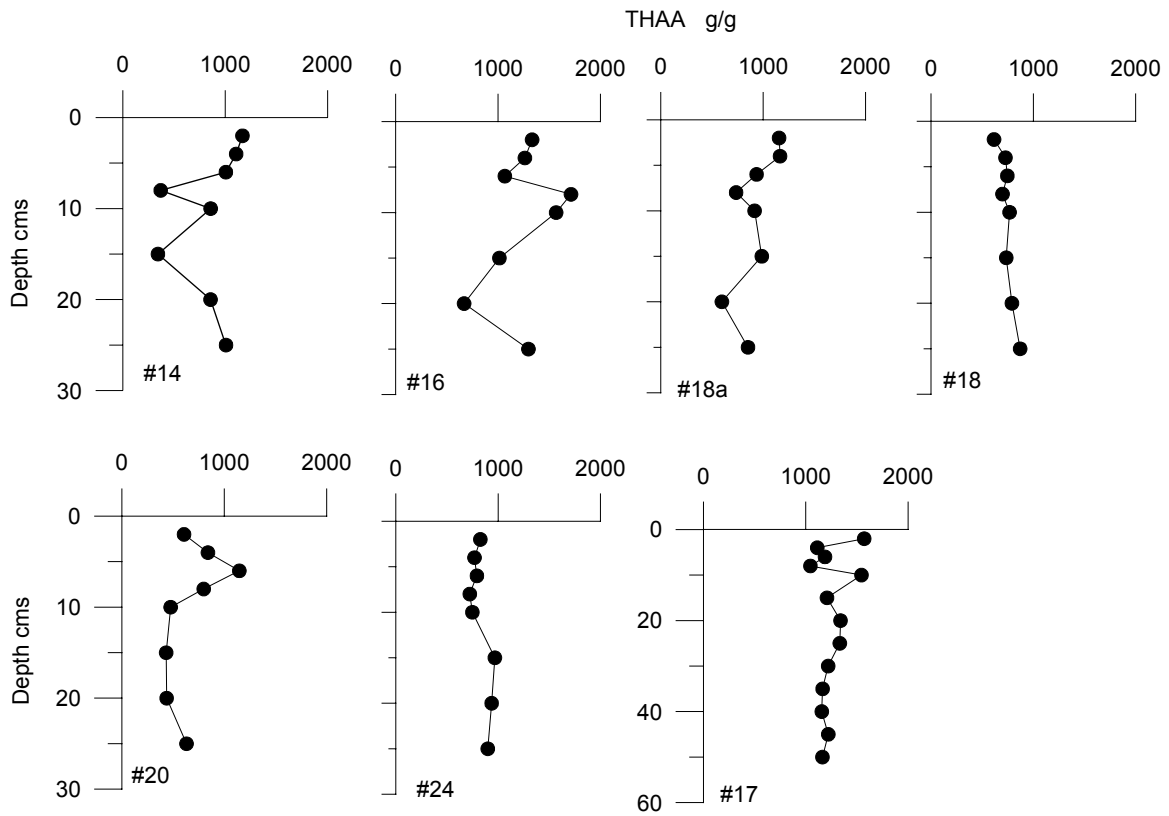


Fig: 11. Amino acid concentration(g/g) in the sediments of the Bay of Bengal

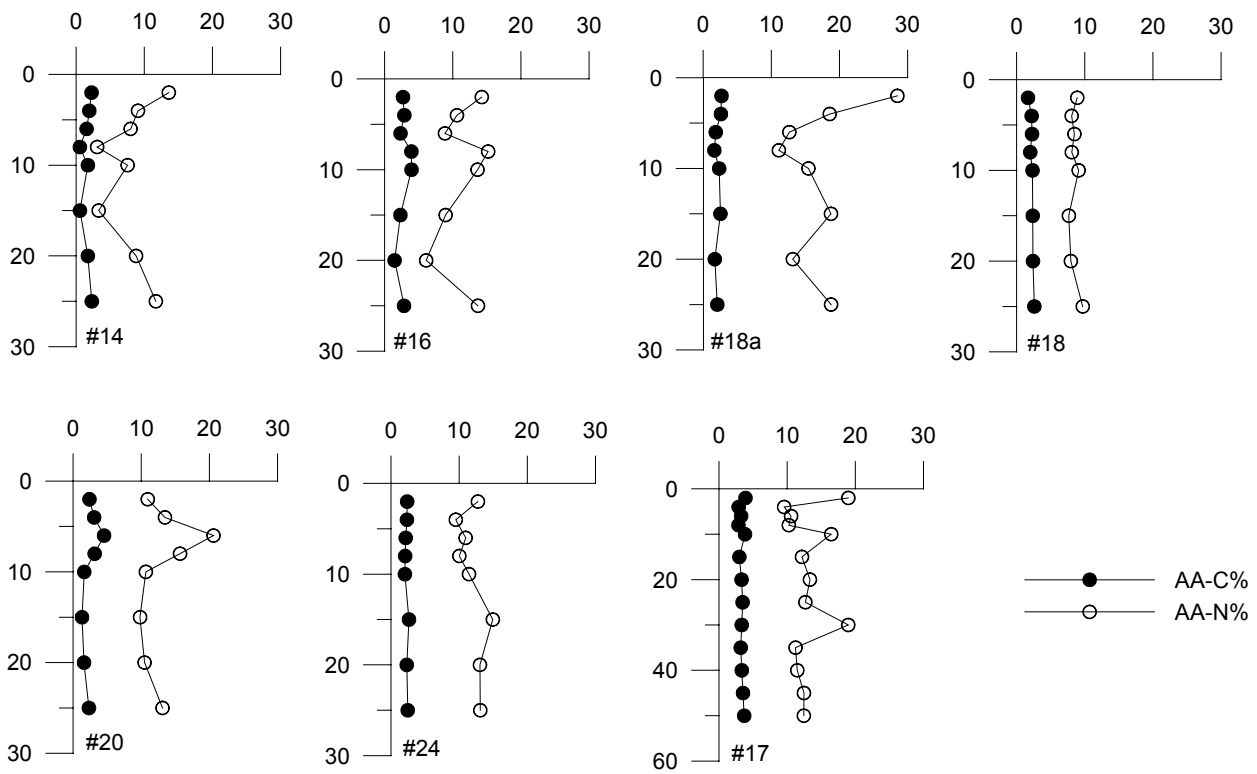


Fig: 12. Amino acid -carbon & amino acid- nitrogen percentages in the sediments of the Bay of Bengal

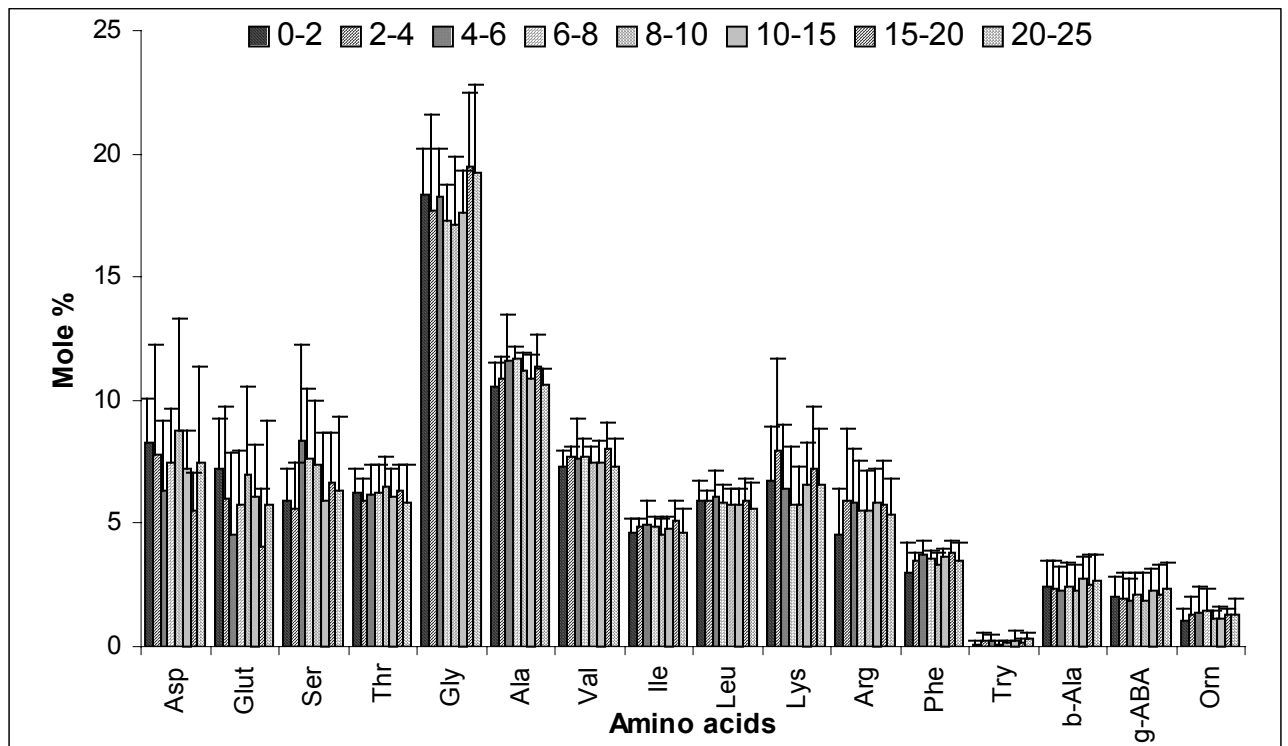


Fig: 13. Composition of amino acids in the Sediments of the Bay of Bengal

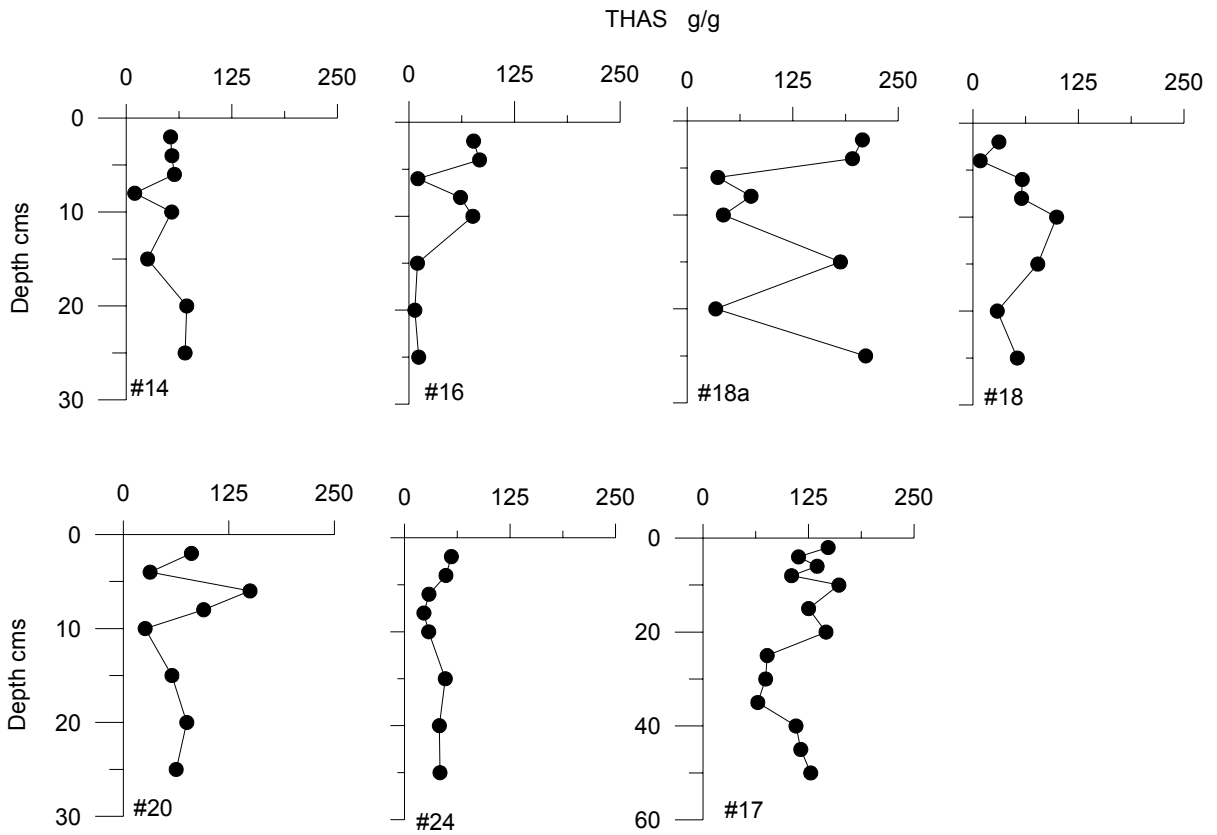


Fig: 14. Amino sugar concentration($\mu\text{g/g}$) in the sediments of the Bay of Bengal

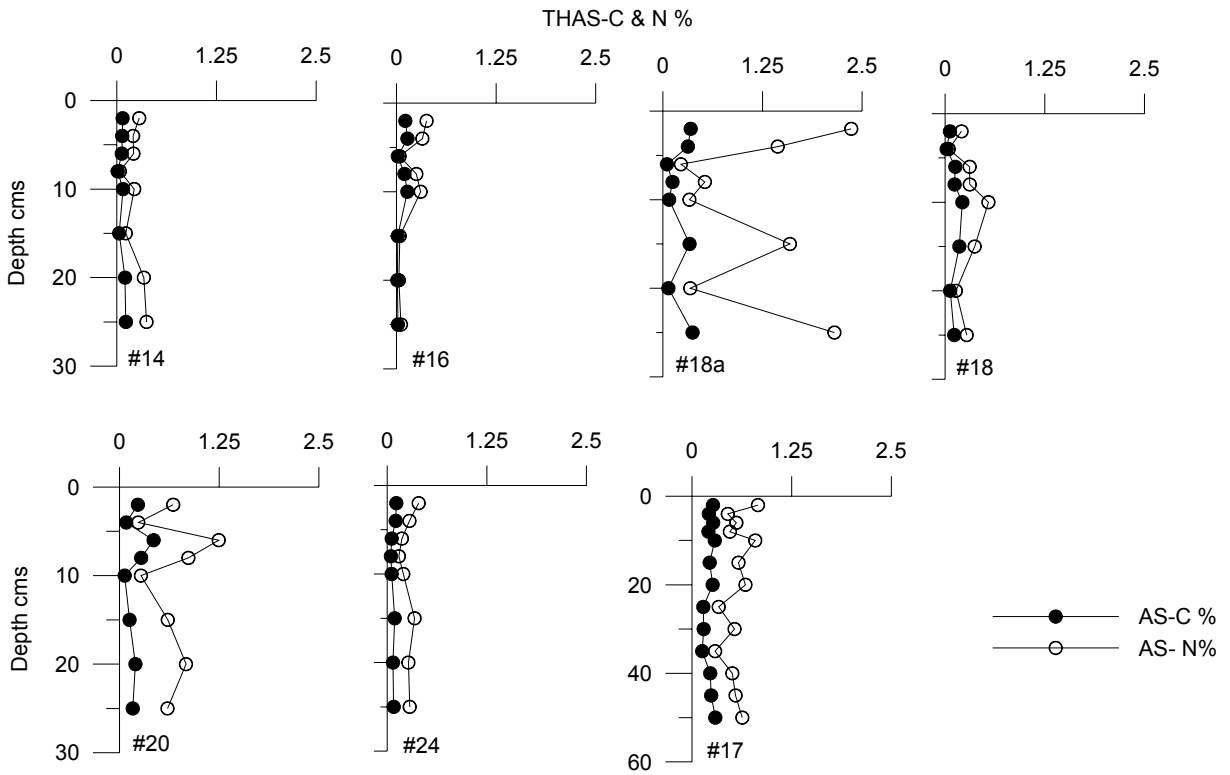


Fig: 15. Amino sugar carbon and nitrogen percentages in the sediment of Bay of Bengal

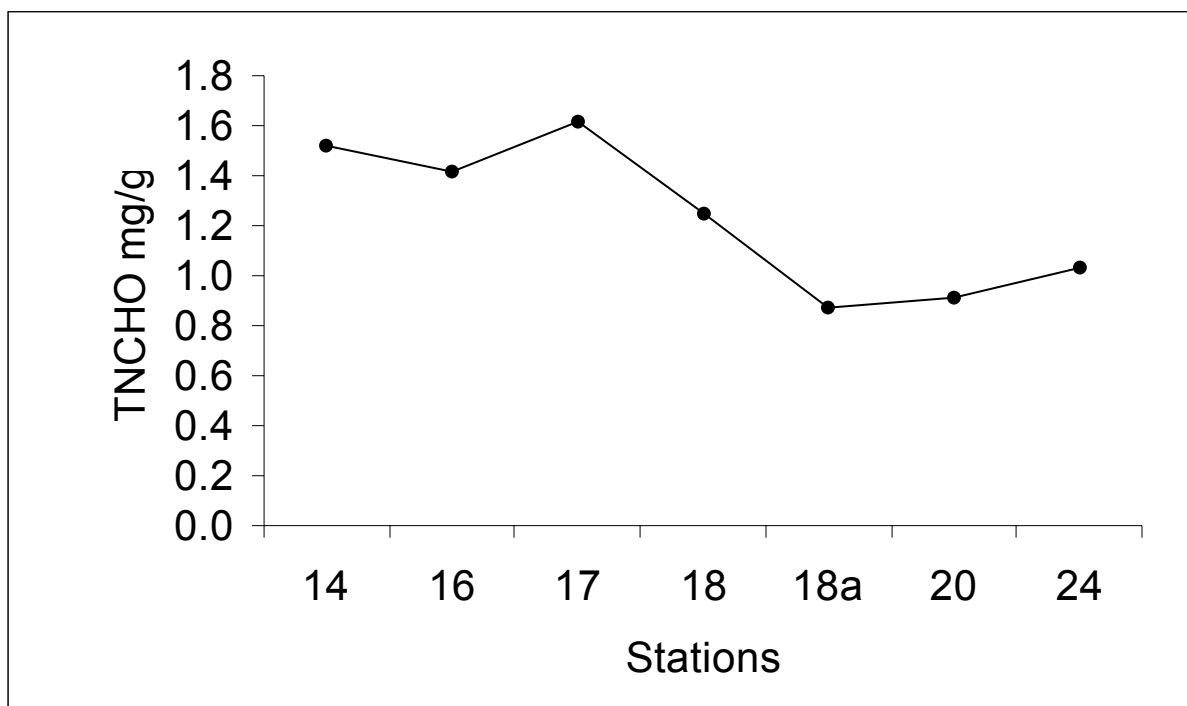


Fig: 16. Concentrations of carbohydrates in the surface sediments of the Bay of Bengal

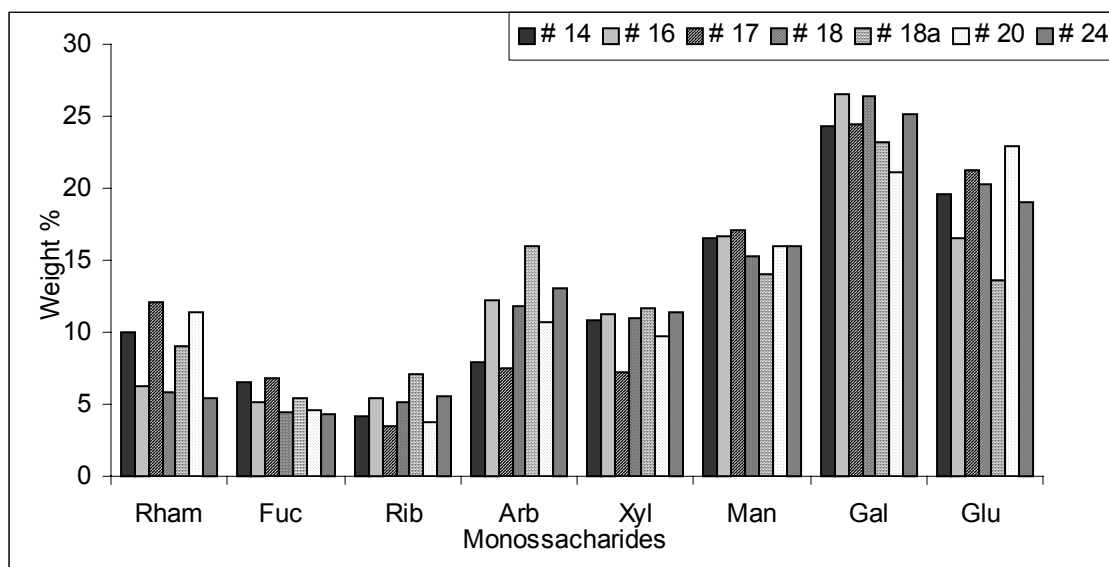


Fig: 17. Monosaccharide composition (Weight %) in the surface sediments of the Bay of Bengal

6. Burial-fluxes

Burial-fluxes and Paleo-fluxes of carbon in the Bay of Bengal.

Participants:

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Objectives

- (1) To estimate present day Burial fluxes of carbon (organic and inorganic) in the northern and western Bay of Bengal.
- (2) To study variations in temperature, salinity, ocean circulation, chemistry and primary productivity changes during the last 22000 years in response to changes in monsoon intensity and freshwater influx.
- (3) To determine the accumulation rates of various elements in sediments and comparison with sediment traps.

Introduction

The net effect on carbon fixation and export on the atmospheric CO₂ concentration has been defined as the “biological pump” (Volk and Hoffert, 1985). It becomes more efficient when nutrient concentrations increase so that more CO₂ is fixed via photosynthesis and/or when the ratio of organic carbon to carbonate carbon (rain ratio) increases for example by the replacement of coccolithophorids by diatoms. The biological pump is also affected by accelerated settling of organic matter by high-density mineral particles (clay minerals and calcite) within marine aggregates (Honjo, 1976; Honjo 1982; Haake and Ittekkot, 1990; Ramaswamy et al., 1991). Globally, opal fluxes are higher in upwelling areas and the westerlies domain (Honjo, 2004) whereas in tropical oceans, carbonates contribute 40 to 80% of the vertical flux (Honjo, 1996). Studies during the last decade suggest that plankton assemblages respond to global change (Sukhanova and Flint, 1998) and coccolithophorids are showing reduced rates of calcification in response to an increase in partial pressure of CO₂ (Riebesell et al., 2000).

The ocean floor is made up mainly of biogenic matter formed in the water column and terrigenous sediments delivered to the ocean as fluvial and eolian sediments. The sediment cover in deeper waters, sometimes thousands of metres thick, is made up mainly of the calcareous or siliceous skeletons of countless tiny planktonic organisms which lived out their lives in the overlying water column and sink to the bottom after death to accumulate slowly at rates of a few millimetres to a few centimetres per thousand years. Along with the above matter a small but significant fraction of organic carbon is also buried. The sediments therefore potentially contain a sort of tape recording of changing conditions in the oceans, and hence also in the Earth's atmosphere over millions of years. If we can read this record, we may not only be able to unravel the past history of the Earth, but also obtain valuable clues about what might happen in the future as a consequence of both natural and man-made changes.

Work carried out

Sediment Traps

Samples from Six PARFLUX Mark VI and Mark VII sediment traps (Honjo and Doherty, 1988) were selected from two sites in the eastern and western Arabian Sea (EAST and WEST), three sites in the northern, central and southern Bay of Bengal (NBBT, CBBT and SBBT) and one site in the Equatorial Indian Ocean (EIOT). In addition, samples from a drifting sediment trap experiment in the Arabian Sea were analysed for POC/²³⁴Th ratios for determining the export flux of carbon.

Sediment core studies

Two gravity sediment cores in the Bay of Bengal, collected during Sagar Kanya Cruise SK-157 have been studied to understand changes in burial fluxes during the last 22000 years.

Methodology

Sediment trap material

Total carbon was measured with a Carlo Erba Elemental Analyser (precision 0.05%). Carbonate percentages were determined with a Wösthoff Carmograph. Organic carbon was calculated as the difference between total and carbonate carbon. Biogenic opal was determined photometrically by a modified version of the method of Mortlock and Froelich (1989).

Determination of planktonic foraminifera, coccolithophorids and diatom fluxes

Organic matter in the sediment trap samples was removed with hydrogen peroxide and disaggregated by ultrasonification for 5 minutes. Foraminifera tests were separated from coccolithophorids by carefully wet sieving with a 25 µm sieve by running deionised water on the sample under low pressure. During sieving, the samples were frequently examined under a microscope to ensure clean separation of the fine and coarse fraction. Foraminifera in the >25µm fraction (including juveniles) were weighed with a Mettler microbalance (to 1 µg), dissolved in dilute hydrochloric acid and titrated with EDTA to get calcium concentration. Similarly, coccolithophorid carbonate in the <25 µm fraction was determined by dissolving the carbonates with dilute hydrochloric acid and estimating the calcium concentrations by EDTA titration.

Biogenic opal fluxes were estimated by extraction with sodium carbonate and determining the silica content by the molybdate blue spectrophotometric method (Mortlock and Froelich, 1989). Large colonial radiolarians, pteropods, ostracods etc. constitute less than 5% of the total flux in our trap samples and were retained in the >1 mm fraction. Biomass of other organisms, having hard parts of opal, are not dominant in the Arabian Sea or the Bay of Bengal. Biogenic opal in the > 25 µm fraction was negligible and below analytical limits in most of the samples. The entire opal flux was therefore taken as equivalent to diatom flux.

Drifting sediment trap samples

One half of the sample was ground with an agate mortar put in a silver foil cup and a few drops

of hydrochloric acid were added to remove carbonates. After drying it was analysed for organic Carbon and total Nitrogen with a Carlo-Erba elemental analyser. The other half of the filter was acid digested (HCl+HNO₃) in the presence of yield spikes and analysed for ²³⁴Th, ²¹⁰Pb ²¹⁰Po following procedures given in Sarin *et al.*, 1992 and 1996.

Sediment core analysis

Gravity sediment cores collected from the deeper portions of the southern and central Bay of Bengal Fan in October 2000 have been analysed for a number of parameters like Bulk and Dry density, Calcium carbonate, Organic carbon and total nitrogen. Selected cores foraminifers have been analysed for delta ¹⁸O and delta ¹⁴C measurement for dating the cores.

Results and discussions

Sediment trap studies

Total annual fluxes in the northern Indian Ocean range between 22.5 and 92.7 g m⁻² y⁻¹. Annual biogenic fluxes at the western Arabian Sea site (>70 g m⁻² y⁻¹) are more than twice that of the other stations. Annual carbonate fluxes are less than 15 g m⁻² y⁻¹ in the Bay of Bengal, between 14 and 20 g m⁻² y⁻¹ at the EAST and EIOT sites and above 35 g m⁻² y⁻¹ in the western Arabian Sea. Opal fluxes, contributed almost entirely by diatoms, are less than 6 g m⁻² y⁻¹ in EIOT and EAST, between 6 and 14 g m⁻² y⁻¹ in the Bay of Bengal and more than 23 g m⁻² y⁻¹ in the Western Arabian Sea. Annual C_{org}/C_{inorg} mole ratios are above 1.6 in the northern and central Bay of Bengal, below 0.8 at the EIOT site and around 1 at SBBT, EIOT, WAST and EAST in the northern Indian Ocean. other sites. Annual Si_{bio}/C_{inorg} mole ratios are above 1 in the northern and central Bay of Bengal and below 1 at other sites. Biogenic carbonate fluxes are especially dominant at the EIOT and EAST sites where annual Si_{bio}/C_{inorg} rain ratios are less than 0.5. Annual Si_{bio}/C_{org} ratios range between 0.7 and 0.9 at all sites except the EAST site, where the ratios fall below 0.5. Sharp temporal variations in rain ratios are seen in the western Arabian Sea, where Si_{bio}/C_{inorg} shows a sharp increase from less than 0.7 during the pre-SW monsoon period to over 2 at the end of the SW monsoon.

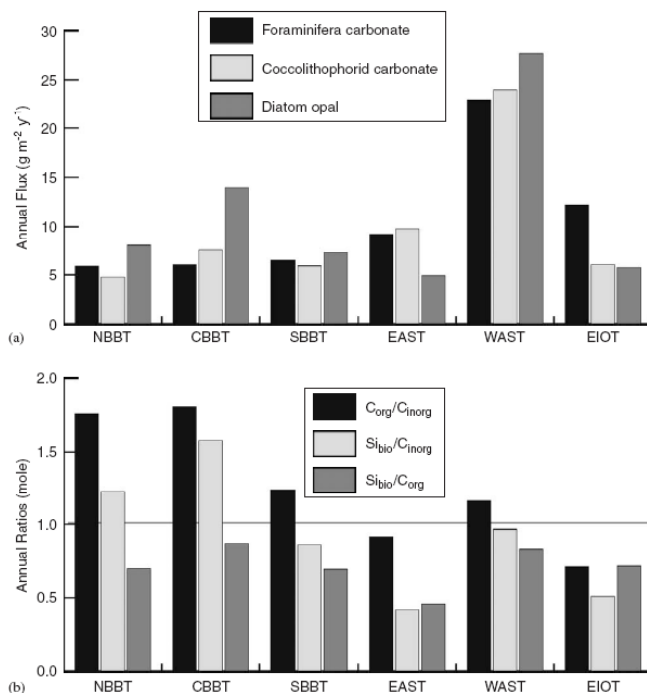


Fig. 1. Annual flux of foraminifera carbonate, coccolithophorid carbonate and diatom opal at the sediment trap locations NBBT, CBBT and molar ratios of $C_{\text{org}}: C_{\text{inorg}}$; $\text{Si}_{\text{bio}}: C_{\text{inorg}}$ and $\text{Si}_{\text{bio}}: C_{\text{org}}$.

Highest annual fluxes of foraminifera carbonate, coccolithophorids carbonate and diatom opal are in the western Arabian Sea. Annual foraminifera carbonate fluxes are greater than $23 \text{ g m}^{-2} \text{ y}^{-1}$ in the western Arabian Sea, moderate at the EIOT site (11 to $13 \text{ g m}^{-2} \text{ y}^{-1}$) and relatively low at other sites (6 to $9 \text{ g m}^{-2} \text{ y}^{-1}$). Annual coccolithophorid fluxes are between 18 and $24 \text{ g m}^{-2} \text{ y}^{-1}$ at the WAST site and at other sites between 4.3 and $10.5 \text{ g m}^{-2} \text{ y}^{-1}$. Annual diatom fluxes in the western Arabian Sea exceed $23 \text{ g m}^{-2} \text{ y}^{-1}$ but are less than $5 \text{ g m}^{-2} \text{ y}^{-1}$ in the Eastern Arabian Sea.

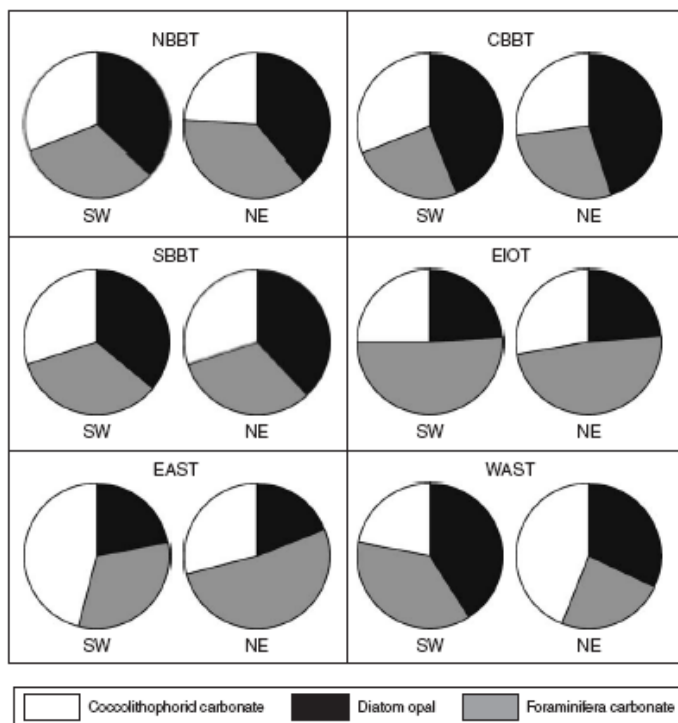


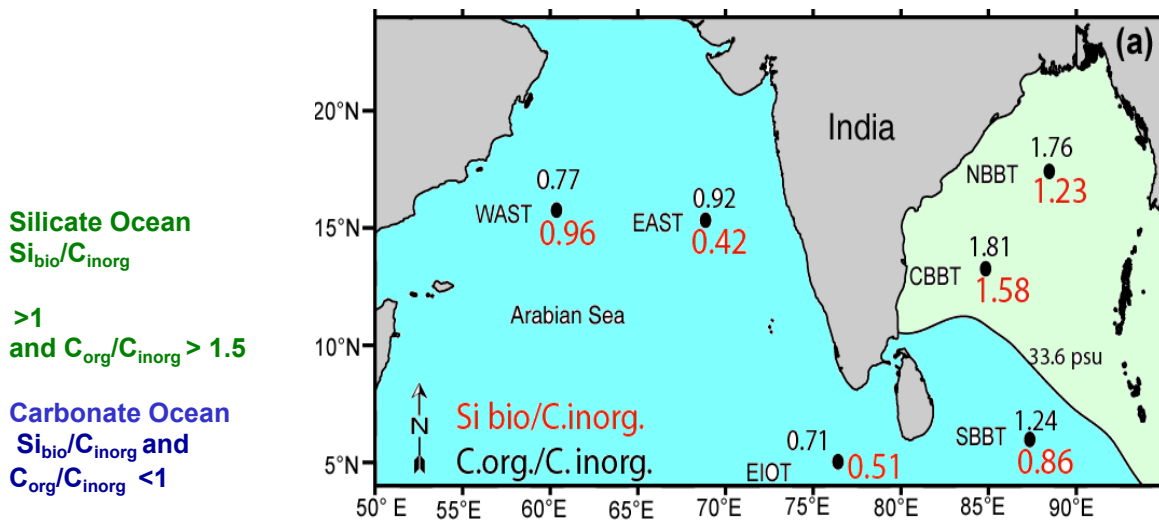
Fig. 2. Pie diagrams showing the relative fluxes of diatom-opal, coccolithophorid carbonate and foraminifera carbonate in sediment trap

Relative flux of major plankton groups

At all three sites in the Bay of Bengal and in the western Arabian Sea, diatoms are the main contributors to biogenic flux (Table 2, Fig. 3 to 10). Coccolithophorids are the dominant contributors to biogenic flux in the eastern Arabian Sea, where they contribute between 30 and 40 % of the annual biogenic flux. In the Equatorial Indian Ocean foraminifera are the dominant material in the sediment traps, where they contribute more than 45% to the total biogenic flux.

Conclusions of the sediment trap study

Based on the composition of settling matter, the oceans can be classified as “carbonate ocean” and “silica ocean”. Carbonate oceans have Si_{bio}/C_{inorg} and C_{org}/C_{inorg} mole ratios that are less than 1 while in silica oceans the ratios are greater than 1. In the “carbonate ocean” surface alkalinity is readily removed by biogenic calcium carbonate particles like foraminifera, coccolithophorids and pteropod tests, while in the “silica ocean” particle fluxes are dominated by opaline particles, which do not affect the surface alkalinity.



Being a tropical ocean, the northern Indian Ocean should normally have been a carbonate ocean. However, monsoon processes push it towards a silica ocean. Our studies confirm the Honjo et al. 1997, report that the western Arabian Sea is a carbonate-dominated ocean punctuated by silica episodes, particularly during the end of the SW monsoon. The eastern Arabian Sea, the equatorial Indian Ocean and southern parts of the Bay of Bengal are carbonate oceans. The northern and central parts of the Bay of Bengal are a silica ocean, where the rain ratios are greater than 1. This is mainly brought about by reduction of foraminifera production, which is severely inhibited by sharp salinity changes during the SW monsoon. Foraminifera play a major role in the rain ratios of settling particles as they are very sensitive to temperature and salinity changes. As a group they are able to adjust to changes in temperature by switching over to new species. However, they are unable to adjust to the large salinity variations present in the Bay of Bengal.

Coccolithophorids are the dominant assemblage during low flux periods but give way to diatoms when silicate levels are high. This may be related to competition in which coccolithophorids are replaced by diatoms or also due to a threshold level of nutrients above which coccolithophorids are not able to survive. This aspect needs further investigation. Enhanced fresh water supply from rivers appears to be a very efficient mechanism of increasing oceanic CO₂ uptake as its silicate supply favors the production of diatoms and its salinity drop produces conditions unfavorable for most planktonic foraminifera species.

Drifting trap studies

Total particulate matter, organic carbon and nitrogen flux

Total particulate matter fluxes measured by drifting sediment traps during February 1997 ranged between 11.9 and 124 mg m⁻² d⁻¹ at 140 m and between 8.9 and 24.6 mg m⁻² d⁻¹ at 300 m. Organic carbon fluxes ranged between 4.08 and 32.2 mg m⁻² d⁻¹ at 140 m and between 1.76 and 5.38 mg m⁻² d⁻¹ at 300 m. Organic carbon percentages ranged between 18 and 32% in shallow traps and between 14 and 22% in deep traps. Total nitrogen was 2.3 to 5.63% in shallow traps and 1.55 to 2.9% in deep traps.

Salp distribution and salp fecal pellet fluxes

The sediment trap material was composed mostly of salp fecal pellets which ranged in size from 2 to 5 mm flakes. The average dry weight of each pellet was 103.7 μg . Sinking rates of salp pellets were between 400 m and 900 m per day. Plankton tow studies show that most of the salps were confined to the upper 30 m with a lesser amount between 30 and 60m. Below 60 m hardly any salps were present. The maximum number of pellets recorded was about 400 pellets per $\text{m}^{-2} \text{d}^{-1}$ on 12 Feb. The deep traps (300 m) located in the sub-oxic layer collected less than 100 pellets $\text{m}^{-2} \text{d}^{-1}$.

^{234}Th activity in the water column

Vertical profiles of total ^{234}Th (dissolved + particulate) on day 1, 4, 8 and 11 do not show much variation during the study period. ^{234}Th activity profiles show low activity in the upper 60 m indicating high particulate material removal from this layer. The total activity of ^{234}Th reaches equilibrium below 150 m. The total integrated ^{234}Th deficiency during the study period (Table 3) was consistently high and range between 2256 and 2357 $\text{dpm m}^{-2} \text{d}^{-1}$.

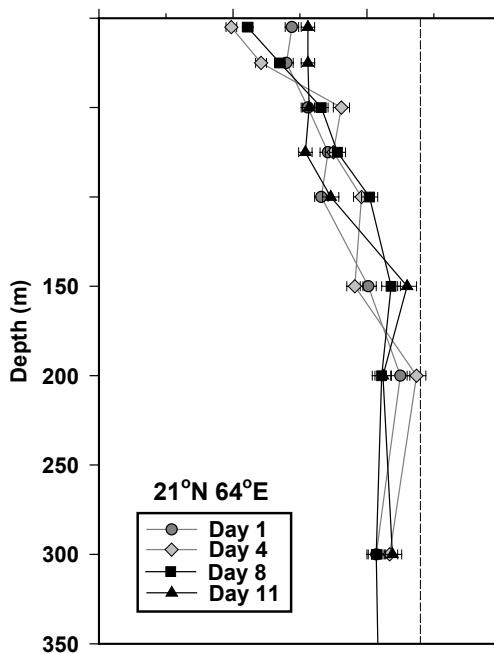


Fig. 4. ^{234}Th profiles in the water column at the 14-day Time Series Station ($21^{\circ}\text{N } 64^{\circ}\text{E}$) during Late NE Monsoon.

^{234}Th specific activity and measured ^{234}Th flux.

^{234}Th specific activity of the sediment trap particles ranged between 1367 and 3445 dpm g^{-1} in the shallow trap and between 1294 and 3910 dpm g^{-1} in the deep trap. Measured ^{234}Th export flux at 140 m ranged between 20.9 to 316.8 $\text{dpm m}^{-2} \text{d}^{-1}$. Measured ^{234}Th fluxes are very low compared to the ^{234}Th deficit in the water column. This suggest that the shallow sediment traps are severely underestimating the actual export flux.

POC/²³⁴Th ratios in settling particles

POC/²³⁴Th ratios in the trapped material varied between 5.4 to 19.8 μmol/dpm. Higher values were seen during the second deployment.

²³⁴Thorium derived export fluxes of carbon

Export flux of carbon was calculated by the following formula

$$\text{C.org Export} = {}^{234}\text{Th export} * \text{POC}/{}^{234}\text{Th}$$

²³⁴Th derived carbon export (Table 3) during our study period is 23 m mol d⁻¹ which is about 29% of the total primary production of 77 m mol C m⁻² d⁻¹.

Buesseler et al., (1997, 1998) have shown that in general the efficiency of biological pump is generally low and export fluxes are usually less than 10% of the primary productivity. Exceptions to this are found during bloom periods when export fluxes can be greater than 75% of the primary production. The Arabian Sea oscillates between very high fluxes during the summer and winter monsoons and very low fluxes during the inter-monsoon periods. While there is a broad agreement that the primary production and export fluxes during the SW monsoon period are high especially towards the end of the SW monsoon. The NE monsoon seems to be characterised by high primary production exceeding 80 m mol g C m⁻² d⁻¹ but it is not clear why long-term studies show low export flux during this period.

Our time-series study conducted over a fortnight towards the end of the NE monsoon during a salp swarm event indicated export fluxes to be 29% of the primary productivity. The observed difference could be due to inter-annual variability and partly due to difference in sampling technique. The high export flux could also have been limited to the two-week period when salps were the dominant zooplankton.

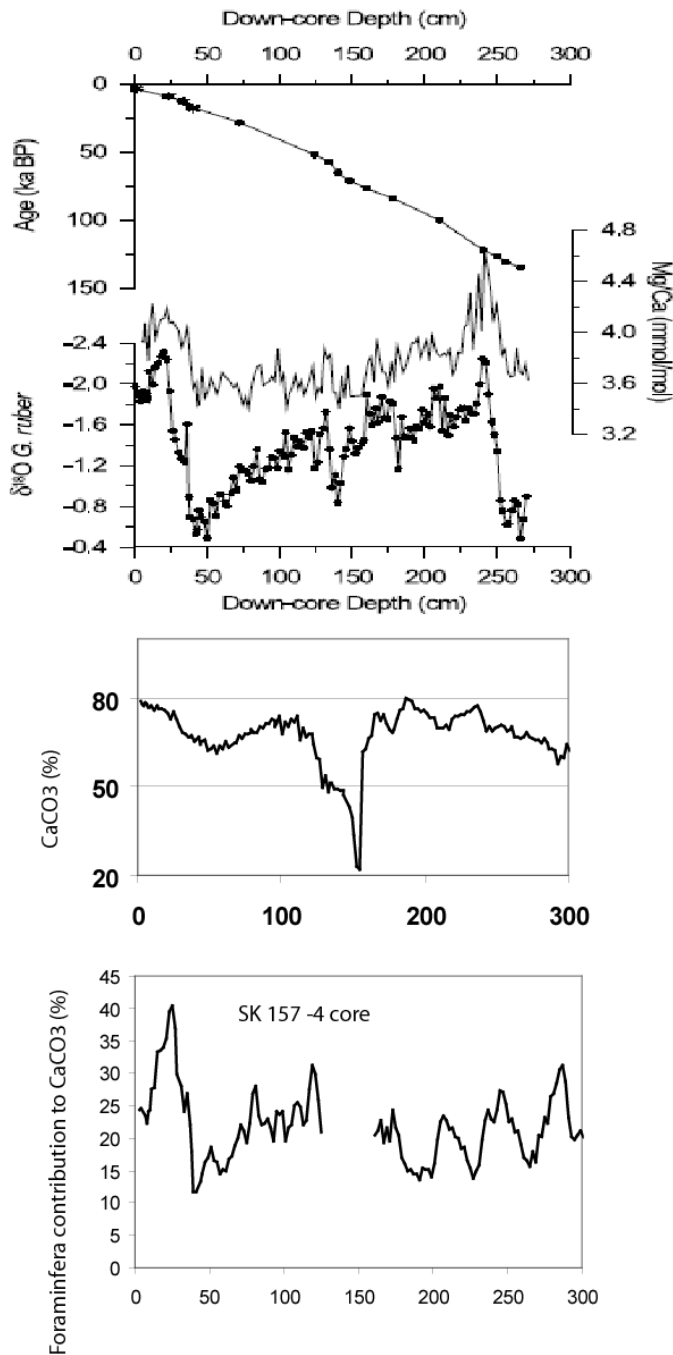


Fig. 5. Down –core variation (smoothened curve) in total carbonate and foraminifera carbonate. Also shown are the isotope stages and dates of the same core from Saraswat et al., 2005. Analysis of Gravity sediment cores collected from the deeper portions of the southern Bay of Bengal Fan show that Calcium carbonate percentages have varied due to salinity and productivity changes as well as dilution due to tremendous deposition of volcanic ash due to the Toba Eruption of 71 KY. Carbonate percentage dropped four fold from an average from 75% to nearly 20%.

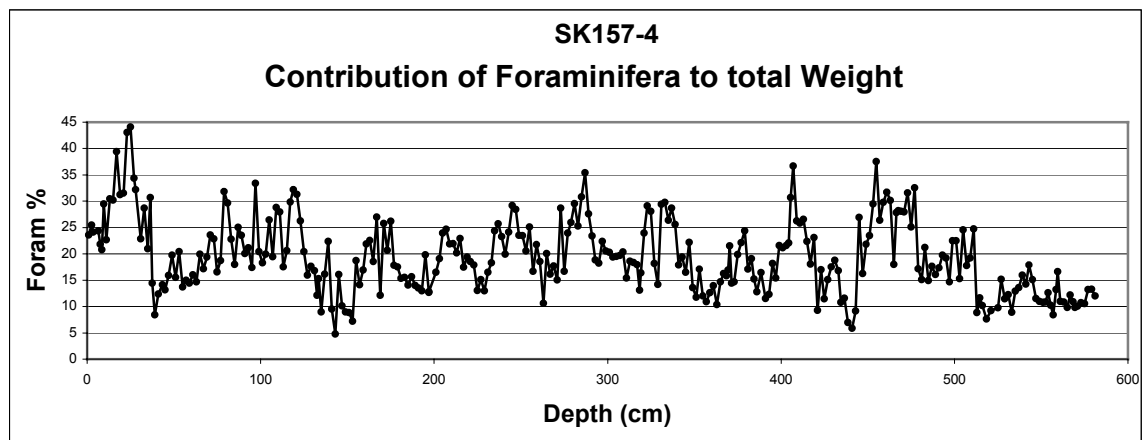


Fig.6. Contribution of foraminifera to total flux in a core from the Bay of Bengal (Sk157/4). Since carbonate percentages did not show much variation due to salinity changes it was decided to look at a more sensitive parameter i.e. foraminiferal carbonate changes. The total foraminifera carbonate was separated by sieving with a 25 micron sieve and calcium carbonate measured using a digital gasometer. Foram weight percentage in the Bay of Bengal has varied from a high of 45% to as low as 5% probably in response to increased salinity during the Holocene due to enhanced precipitation and freshwater influx from rivers. This proxy is very promising excellent proxy for changes in monsoon intensity in the past as it resembles the SPECMAP curve to a very high degree. Comparison of the equatorial Indian Ocean foraminifera carbonate curve with that of the Pacific Ocean SST variation show a remarkable similarity between the two oceans. This suggests the possibility of a common mechanism regulating the Indian Ocean and Pacific Ocean temperature and productivity over larger time scales.

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7. Data Management

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Introduction

NIO-data centre (Nationally and Internationally known as IODC) was born in 1964 along with the institute as National Oceanographic Data Centre (NODC) under the IOC/IODE data centre network.

Department of Ocean Development (DOD) recognized IODC as one of the 14 National Marine Data Centres (NMDCs) in 1994. IOC/IODE recognized IODC as Responsible National Oceanographic Data Centre for the Indian Ocean (RNODC-INDO) in 1996.

Ever since the establishment of IODC, it has been actively involved in delayed mode data management (the mandate set for the centre by the institute) for oceanographic parameters with emphasis on the following aspects that are mandatory for a data centre:

- Data acquisition
- Database development
- Services to user community (Data/information dissemination)
- Basic research in data quality control & Management
- Development of value added products such as data reports, atlases, CDs, etc
- Basic research using available data archive at the centre.

The Bay of Bengal Process Studies (BOBPS) is a multidisciplinary programme, involving many scientific groups from different organisations. To ensure quality data archival and efficient dissemination both for various groups and to other user community, it is required to have a well coordinated data management system under the BOBPS. Thus this group's activities will include; data and meta data acquisition from various scientific groups, general quality checks, data formatting, data base creation and user oriented request handling. IODC, using its expertise in data & information management, can provide data services to meet the objectives of BOBPS. Major task will be of incorporating the meta-data along with other quality flags for the multidisciplinary data. In addition, by supplementing with other existing data archive in the centre, we aim a value-added database management system for the BOBPS program.

Data acquisition

The following BOBPS cruises data sets have been acquired and database has been developed:

Cruise No.	Period	No. of Stn.	Parameters
Sk-166	02.07.01 to 02.08.01	41	CTD,XBT,CHEM, BIO, S-ME, MBIO etc
SK-182	14.09.02 TO 12.10.02	41	CTD, CHEM,BIO, S-MET, MBIO etc
SK-191	12.04.03 TO 07.05.03	34	CTD, CHEM, BIO, MBIO, S-MET etc

Data Processing

BOBPS Cruises and Historical oceanographic data sets for the region have been processed and database has been developed as per the project objectives and scientist requirement. Metadata for 116 BOBPS stations data have been process for developing the station inventory level information, Data/information on CTD, chemical and biological parameters have been processed for above cruises and data base for BOBPS was updated. Historical oceanographic data sets with in BOBPS area have been retrieved for developing the BOBPS CDROM.

Web site for BOBPS: (Lay out of the home page is at Annex-1)

An interactive web site is being developed to provide online information about the BOBPS project. It contains the information regarding the BOBPS objectives, various sub-projects, cruises undertaken and parameters measured, salient results, up-coming events, cruises and progress reports etc. Any one can get the BOBPS project information from the web site the URL is:

<http://www.indian-ocean.org/bobps/>

Data visualization /Quality control S/W

A window-based, User's friendly data/information retrieval and visualization software has been developed. The system is developed in Visual Basic (VB) and it has three modules namely selection, visualization and retrieval of data sets. The selected data profiles can be plotted by visualization module. The module also plots average profile of the variable considering all the stations of the cruise and overlay a profile of the station. The system will be interfaced with BOBPS project data and historical data sets available with IODC in the region. The BOBPS CDROM development work yet to be completed.

BIO data quality control

A quality control system has been developed and the quality control (qc) checks has been performed on the primary production (pp), and chlorophyll-a (chl-a) profiles in the Northern Indian Ocean collected during 1976 to 1997 by R.V. Gaveshani cruises (1976-94), and ORV Sagar Kanya cruises (1985-1997). These quality checks are based on the inventory, duplicates, ranges, maximum value of specific production, and tail end increase etc. Preliminary quality check is performed by visual inspection of the vertical profiles of pp and chla along with temperature. Other quality check on pp was done by computing the chla specific pp. Statistical check were carried out by grouping the data in $1^0 \times 1^0$ Or $2^0 \times 2^0$ Latitude-longitude square depending on the number of data sets available. Mean and standard deviation (SD) for the values from each depth were computed irrespective of the season. Maximum and minimum value for each depth were fixed as mean $\pm 5SD$ when land area contained in the square. In other case area the maximum and minimum value were fixed as mean $\pm 3SD$. Below 50m depth the criteria set was that the value should be between mean $\pm 3SD$.

Work to be completed

BOBPS CD

BOBPS CD work is to be completed. Since last BOBPS cruise was under taken very late, therefore the data processing work and related work of the project was further delay.

The BOBPS CD will contains data/ information pertaining to the BOBPS programme. This programme was multidisciplinary approach jointly conducted by four national agencies. The field campaign in the Bay of Bangel was conducted between 2001-2005 in 5 cruises on board ORV Sagar kanya and Sagar Sampatha. Interfaces software was developed for data selection, visualization and retrieval form the CD.

The CD will contains BOBPS project data sets and historical data profiles collected by NIO and World Data Centre in the region. These profiles are on temperature, salinity, dissolved oxygen, nitrate, nitrite, phosphate, ammonia, silicate, pH and alkalinity, chlorophyll-a, Primary production etc. in the Bay of Bengal region.

8. Modelling

Modelling of Biogeochemical Cycles in Bay of Bengal

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K.S.Yajnik

Objectives

- .1 To continue to develop and apply zero and one-dimensional models of the marine ecosystem with special reference to Bay of Bengal. This is a crucial aspect of the study as it will provide valuable inputs to large scale simulation of the biogeochemical cycles in the Bay of Bengal.
- .2 Development of chemical models to include detailed carbon chemistry and pH.
- .3 Integration of the marine ecosystem model and the chemical model with a large scale ocean circulation model. This is a key step towards synthesising data to make inferences about basin-wide transfer of carbon fluxes across the air-sea interface.
- .4 Comparison and validation of models using both *insitu* data collected from JGOFS data and large scale spatial and temporal data provided by satellites, especially SeaWifs, IRS-P3 and other ocean colour monitoring satellites.
- .5 Synthesis of all the knowledge and data obtained in the Indian JGOFS programme to yield a comprehensive picture

Introduction

Arabian Sea and Bay of Bengal are the adjoining seas of Indian Subcontinent, having similar terrain. They are relatively small ocean basins located in the tropical region and are influenced by the reversing monsoon winds. The physical, chemical and biological features of the Bay of Bengal are significantly different from the Arabian Sea because of (i) enormous supply of fresh water and the associated sediment load from large rivers of the Indian peninsula, (ii) the Bay of Bengal is partially connected to Pacific. The fresh water input reduces the surface salinity but brings in new nutrients which forms a strong stratified layer hampering exchange processes between atmosphere, surface and deep waters. The available data also show that the Bay of Bengal is less productive though there is large riverine import of nutrients. The cyclones in the Bay of Bengal, especially during May and October, are expected to affect heat and buoyancy fluxes dramatically over a very short span of time, triggering associated changes, which are not yet quantified in water column chemistry and biology. Precipitation is more than evaporation in the Bay of Bengal, which influences chemistry and biology. The effects of all these processes on carbon cycle needs to be studied. The Bay of Bengal is grossly under-sampled and poorly understood.

Background

Studies on marine biogeochemical cycles form an important component in the coupled ocean-atmosphere models for climate studies. Major challenges in the marine biogeochemical modelling are (a) the identification of the ecosystem compartments, the underlying biogeochemical processes and their parametrizations (b) model-data comparisons and (c) data assimilation studies.

The complexities involved in the modelling of the marine ecosystem are the choice of state variables, the selection of significant biological, chemical and physical processes, the nature of the available data needed for simulation, parameter estimation, validation through systematic comparison of simulation results and data, and data assimilation. The contemporary models contain three to eleven state variables depending on the focus of study. The basic model consists of phytoplankton, zooplankton and nutrients as three state variables and the processes like growth, mortality, grazing, excretion and external forcing functions like seasonal variation of mixed layer depth and solar radiation. All the processes influencing the ecosystem dynamics have various model formulations and typically have a large number of model parameters. As a part of these studies, in the earlier phase of the Indian JGOFS programme at C-MMACS, primary production in the Arabian Sea was studied in detail, since high spatial and temporal variability of various physical processes and abundance of nutrients is observed in the Arabian Sea. Since growth and grazing functions are intrinsically nonlinear, the nonlinear dynamics of the marine ecosystem was studied. Also, parameter sensitivity analysis was carried out for a contemporary seven component model in the mixed layer. A general methodology of comparing the results of simulations with observations was developed to enable model refinements and fine tuning of parameters. In order to get realistic simulations, some modifications were introduced in the phytoplankton growth term in the FDM (Fasham et al., 1990) model. These modifications included the diurnal variation of solar radiation, seasonal variation of daylength at different locations in Arabian Sea and different formulations for the uptake by phytoplankton in a multi-nutrient environment.

The Method

The model simulations are carried out using the contemporary model of marine ecosystem for the mixed layer (FDM model) consisting of seven components for the Arabian Sea (AS) where data are available from JGOFS, and the Bay of Bengal (BOB) where the observations are being carried out under BOBPS. The simulations aim to understand

1. The effect of the formulation of uptake by phytoplankton in two-nutrient environment on the dynamics of marine ecosystem.
2. The influence of the values of model parameters on biology and chemistry of the ocean
3. The effect of biological processes on the carbon flux across the ocean surface

Physical Model

The marine ecosystem model is coupled with the physical model (MOM) to carry out 3-D simulations in the North Indian Ocean. The computation domain for the physical model is 15° S to 30° N with resolution varying from 1° at 15° S to 0.4° north of equator, 37.6° E to 100° E with a resolution of 0.4° and there are 35 vertical levels (10m in the upper 100m).

One set of physical model simulations are carried out using 6-hourly wind forcing (NCEP data), to compare the upper ocean thermal structure and salinity, with the available observations under the BOBPS programme for the years 2001 to 2003. Other set of physical model simulations are carried out using the climatological forcings.

The physical model (Modular Ocean Model 2.2) is forced with monthly climatological COADS winds, heat and precipitation minus evaporation (pme) fluxes. Solar fluxes are from the Oberhuber database (1988). The initial temperature and salinity profiles (annual averages) are from the Levitus database (1994). A combination of restoring (time scale 30 days) and prescribed fluxes are applied at the top surface for temperature and salinity. Many experiments at GFDL (Gnanadesikan, personal communication) have shown that the use of diagnostic heat and salt fluxes from equilibrium runs of ocean models is very effective in reducing the imbalance between the imposed fluxes and the model-computed fluxes. We have therefore taken monthly fluxes from a 50 year run as input to our model. There is a remarkable similarity between these fluxes and the climatic atlases of Hastenrath et al. (1989), especially for the heat fluxes. Solar penetration is parameterized with a double exponential following Paulson and Simpson (1977). The Pacanowski-Philander parameterization (1981) for vertical mixing, which is based on increasing the vertical mixing coefficient (up to 50 cm² s⁻¹) in regions of marginal stability, is used. In addition, explicit convection is also applied to completely homogenize unstable vertical density gradients. A rigid-lid formulation for the barotropic mode is used. The quicker algorithm (Leonard, 1979) is used for the advective transport of heat, salt and all the ecosystem components. Horizontal diffusion is parameterized as a Laplacian with eddy diffusivity for momentum and heat. The time step in the model is 2700 s for tracer, baroclinic and stream function equations.

Biological and Chemical Model

Recent experiments on nitrogen dynamics by McCarthy et al. (1999) in the Indian Ocean have thrown new light on several aspects of nitrogen uptake by phytoplankton. In particular, the inhibitory effect of ammonium on the uptake of nitrate displays the properties of similarity and saturation with increasing ammonium. Since the five types of two nutrient interaction relations currently in use, proposed by Jasmart et al (1977), Wroblewski (1977), Parker (1993), Walsh (1975), Taylor and Joint (1990), describing the growth of phytoplankton, have at most one of the properties, either similarity or hyperbolicity, a rather general theoretical formulation was proposed for uptake of nutrients in a multi-nutrient environment. It is phenomenological in character with similarity and hyperbolicity taken as basic properties. The generality of the framework offers possibilities of applications to other multi-nutrient environments. All the six two-nutrient interaction relations were introduced into the seven component marine ecosystem model (Fasham et al., 1990), to study the effect of this formulation on the behaviour of the biogeochemical variables in the mixed layer. The monthly average values of chlorophyll obtained from mixed layer model simulations at a few stations in Bay of Bengal and Arabian Sea were compared with SeaWiFS data. Seasonal variation of different variables and fluxes for all the formulations were studied to understand the effect of different formulations of the ammonium inhibition of the nitrate uptake by phytoplankton on the marine ecosystem dynamics. Since the simulation results were found to be highly sensitive to the parameter values used in the ammonium inhibition relations, some optimization schemes are being applied to obtain parameter values leading to more realistic simulation results.

The two nutrient interaction laws currently in use (WR-Wroblewski Relation and ON-O'Neill Relation), and a new general formulation based on the properties of similarity and hyperbolicity (YS, Yajnik and Sharada, 2003), were introduced into the seven component marine ecosystem model (Fasham et al., 1990). This model was coupled to the physical model with climatological forcing (Sarmiento et al., 1993, Swathi et al., 2000) to understand the consequences of selection of kinetic relations on 3D simulations of the coupled physical-biological model.

Chemical tracers (dissolved inorganic carbon (DIC) and alkalinity (ALK)), are introduced in the coupled physical-biological model to understand the influence of biology on chemistry on a basin-wide scale. Phytoplankton is the only carbon fixing component in the whole system. The formation of biogenic calcium carbonate is also considered. To convert the ecosystem variables from nitrogen to carbon units, a constant value of Redfield ratio (C:N = 7) is used. The DIC and ALK fields are initialized using the objectively interpolated atlas of Myrmehl and Drange (1998). To determine the transfer of CO₂ across the air-sea interface, DIC is partitioned into three species, namely, the dissolved CO₂ component (pCO₂), HCO₃³⁻ and CO₃²⁻. Boric acid is taken to be proportional to the salinity, but phosphoric acid and silicic acid are not included. The equilibrium model of Peng et al. (1987) is used with some modifications to compute pCO₂. Since the chemical model calculations are compute intensive, they are carried out only for surface grid points. The flux of CO₂ across the air-sea interface (F) is computed using the equation

$$F = k_l \alpha_s (pCO_2^{air} - pCO_2^{sea})$$

where k_l is the piston or transfer velocity and α_s is the solubility of CO₂ in sea water. pCO₂ for air has been adjusted for 100% relative humidity. The piston velocity, which is regulated by the

turbulence at the air-sea interface and chemical reactions in the liquid phase, is calculated using the Wanninkhof (1992) formulation. In contrast to other biological and chemical species, the flux F is added to the top grid box during the solution of the DIC equation.

Results and Discussion

Physical Model Simulations using Climatological Data

The physical model simulations are run for six years with climatological forcing, and biological model (modified version of FDM, 1990) is introduced. The coupled physical-biological model is run for four years and then the chemical model (Peng et al., 1987) is coupled to the physical-biological model. The coupled physical-biological-chemical model simulations are carried out for four years. The results of the fourth year simulation of the coupled physical-biological-chemical model are analysed in detail. Many of the parameters used for the biological model are taken from FDM, 1990 and the parameters for uptake kinetics are taken from McCarthy et al., 1999. The chemical model parameters are taken from Peng et al., 1987.

Summary of Physical Model Results

The mixed layer depths (MLD) from the physical model with climatological forcing showed very good agreement (to within 20 m in most places) with the Levitus atlas (1994) in January, while the agreement off the Somali coast was not as good, in July, possibly due to strong winds. The model heat fluxes were very similar to the imposed surface heat fluxes, indicating that the model needed very little restoring flux to keep sea surface temperatures from drifting. The comparison between model and data for salinity showed very good agreement in the Arabian Sea except near the southern tip of India while it was middling in the Bay of Bengal. Almost all the known models today have difficulty in simulating thermal and salinity structures properly in the Bay of Bengal. The present model is no exception. The large river influx, which is not modelled explicitly but indirectly by restoring salinity and the sediment load are possible reasons. (For details, see Sharada et al., 2005).

Summary of Physical_Biological Model Results for the Arabian Sea

The profiles obtained from the three simulations (using three different kinetic relations for uptake) of the physical-biological coupled model were compared with those obtained from JGOFS cruise data (US JGOFS Home page) at one of the JGOFS stations S4 (19°N, 59°E) in Arabian Sea during six times during a year. It was seen that WR relation gave the largest departures from observed nitrate as it tends to overestimate ammonium inhibition. The YS relation gave the smallest departure as it is the most accurate. The flat portions in the simulated profiles for the upper layers in winter and in monsoon were due to the treatment of deep convective mixing in the model. The chlorophyll profiles at the same station for the simulations and the JGOFS data were in reasonable agreement for all the cases except for April and September. None of the relations was able to capture subsurface chlorophyll maxima. While the values given by the three relations were comparable, those given by YS relation appear slightly closer to the observed values. Primary productivity profiles at the same station showed that YS relation generally gave values closest to observations. WR relation gave the lowest values of primary productivity which was consistent with the lower drawdown of nitrate. It was also noted

that the agreement with the experimental data in the YS simulations appeared to be significantly better than what has been recently reported by Kawamiya and Oschlies (2003) using a four component biological model (See for details, Sharada et al., 2005).

The annually averaged primary production for the three kinetic relations were compared with SeaWiFS data. The YS relation gave the highest productivity and the WR relation gave the lowest. The YS relation, which generated about 350-400 gC m²/ year in the Northern Arabian Sea, showed excellent agreement with SeaWiFS-derived annual productivity calculated by Behrenfeld and Falkowski (1997) (Yajnik et al., 2003).

The annually averaged *f*-ratio (the ratio of new to total production) was about 0.3-0.4 in the main production areas in the northwestern coastal region with much lower values in rest of the basin. Regenerated production was the main component of primary production as was observed in the mixed layer model (Sharada & Yajnik, 1997). The annually averaged particulate export ratio was about 0.2-0.25 in the high production regions.

Coupled Model Results for Bay of Bengal

The coupled model simulation results (YS) are analysed in detail for the 88°E transect in Bay of Bengal with one set of parameter values (Basic Experiment - exp3). Chlorophyll values at 5m depth for four stations on 88° E transect show that there is no significant seasonal variation and latitudinal variation. Chlorophyll values at 55m depth show significant seasonal variation and also latitudinal variation. This variation may be because of the presence of deep chlorophyll maxima.

The contour plots of chlorophyll and nitrate for four months (July to October) show that there are no significant spatial and seasonal variations on the open ocean (88° E) transect in the upper parts of the Bay of Bengal. Nitrate (monthly average) profiles for July, obtained from the model simulations, have a sharper nitracline than that in cruise (snapshot) data. The processes below the euphotic zone need to be examined more carefully in the model.

Coupled Physical-Biological-Chemical Model Results for AS and BOB

To determine the role of the biological pump, one numerical experiment (basic experiment) was chosen as the most appropriate representative of the present biological model. The parameter values used in this experiment are given in the Table 1. The seasonal variation was studied by considering averages in four seasons, namely, South West Monsoon (June, July & August, SWM), North East Monsoon (December, January & February, NEM), Spring Inter Monsoon (March, April & May, SIM) and Fall Inter Monsoon (September, October & November, FIM). The 88° E was selected for BOB and 65° E was selected for AS.

Latitudinal variation of the surface pCO₂ in biotic (Physical-Biological-Chemical model) and abiotic (Physical-Chemical model) simulations for the 88° E (BOB) and 65° E (AS), for July to October shows that Surface pCO₂ is typically greater in the biotic simulations than in the abiotic simulations, during July to October. Also, pCO₂ is more in AS than in BOB except in a small equatorial region in the BOB. Furthermore, the surface pCO₂ is always greater than the atmospheric pCO₂ (360 matm). Therefore, the ocean is outgassing at all locations on 88° E and 65° E transects in both abiotic and biotic simulations during July to October.

Latitudinal variation of Carbon Flux (cfl) at the surface of the ocean obtained from both biotic and abiotic simulations for the 88° E (BOB) and 65° E (AS), for July to October showed that Carbon flux from the ocean to the atmosphere is significantly greater for the biotic case, in BOB as well as AS, than the abiotic case. Transfer of Carbon is maximum during August in AS. Biological and Physical pumps make comparable contributions to carbon flux in BOB and AS.

Since the results of the simulations carried out for a set of parameters with the YS relation for the nitrate uptake (Basic Experiment - exp3) show that pCO₂ at the surface for biotic simulations are more than that of abiotic simulations for all seasons, on two transects, one each in AS and BOB, which is contrary to the expectations, a question arose whether the parameter values were responsible for these counter intuitive simulation results. It is seen that the values of primary productivity and chlorophyll obtained from the basic experiment compared well with the US JGOFS observations at a few locations in AS and also with SeaWiFS data, but the concentrations of Ammonium and Zooplankton obtained from this model simulation are very high compared to the observations, which are contributing to the high values of DIC or pCO₂. Therefore, a detailed study of the source and sink terms of the tracers DIC and ALK and sensitivity of the parameters related to the regeneration of Ammonium (or DIC) by zooplankton and bacteria, and grazing by zooplankton to the ecosystem dynamics and carbon flux is carried out.

Numerical Experiments - Parameter Sensitivity

Based on some understanding of the values of a few of the model parameters, around 20 numerical experiments for the coupled physical-biological model and around 10 experiments for the coupled physical-biological-chemical model are carried out for different sets of parameter values, and a detailed analysis of the concentrations of variables and the fluxes are being done. Table 1 gives the details of nine numerical experiments which are chosen for detailed analysis and the parameter values used for simulations.

Spatial and temporal variations of chlorophyll and primary productivity obtained from SeaWiFS data are compared with the model results for all the numerical experiments, to see whether the model results are within the expected range. The profiles of chlorophyll and primary productivity obtained from the nine model simulations are compared with the BOBPS cruise data for three seasons, namely, Spring Inter Monsoon (SIM), South West Monsoon (SWM) and Fall Inter Monsoon (FIM).

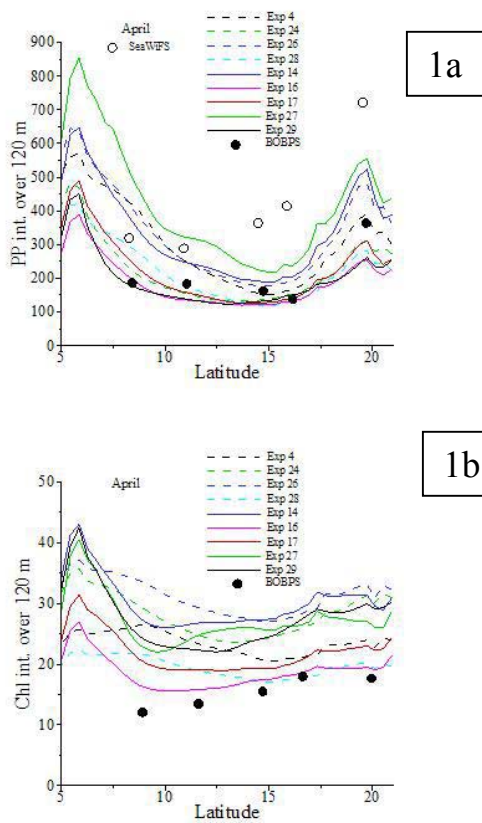
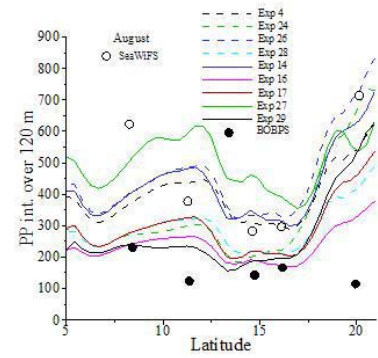


Fig. 1 Depth integrated (a) PP ($\text{mg C/m}^2/\text{day}$) and (b) Chl values (mg Chl/m^2) from different model simulations compared with the BOBPS data and SeaWiFS data during SIM

Depth integrated values of primary productivity and chlorophyll on the 88° E transect obtained from nine model simulations are compared with the BOBPS cruise data and SeaWiFS data for the three seasons, SIM, SWM and FIM. Fig.1a shows the comparison of depth integrated values of PP obtained from nine model simulations with the BOBPS cruise data as well as SeaWiFS data on the open ocean transect during SIM. All the model simulations and the observations show that PP is lower in central parts of BOB in the open ocean during SIM. All the simulations did capture the trend seen in the observations.

Depth integrated values of chlorophyll on the 88° E transect obtained from nine model simulations are compared with the BOBPS cruise data for SIM (Fig.1b). It is noted that the model chlorophyll values agree well with the observed values along the transect only for a few model experiments. Depth integrated chlorophyll values for all the model simulations do not show significant latitudinal variation in the open ocean. Though all the simulations could capture the trend seen in the observations, the values of chlorophyll obtained from many of the models are much higher than the observed values.

Fig. 2a shows the comparison of depth integrated values of PP obtained from nine model simulations with the BOBPS cruise data and SeaWiFS data on the open ocean transect during SWM. Most of the model simulations and the SeaWiFS data show that PP is less in central parts of BOB in the open ocean. All the models capture the trend seen in SeaWiFS data.



2a

Fig. 2b shows the comparison of depth integrated values of Chlorophyll obtained from nine model simulations with the BOBPS cruise data on the open ocean transect during SWM. All the model simulations and the observations show that depth integrated chlorophyll values do not have significant latitudinal variability in the open ocean. Though all the simulations capture the trend seen in the observations, the values of chlorophyll obtained from all the simulations are much higher than the observed values.

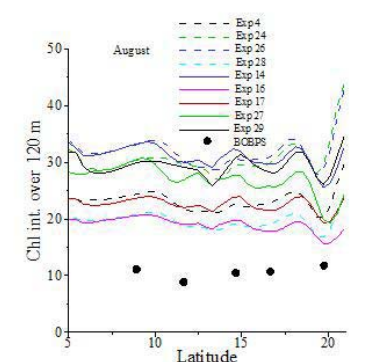
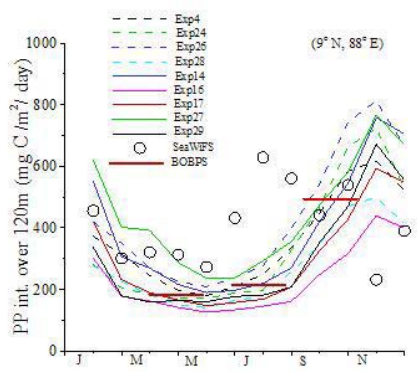
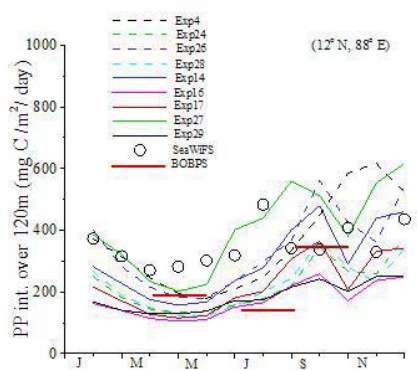


Fig.2 Depth (b) Chl (mg simulations compared with the BOBPS data and SeaWiFS data during SWM.



3a



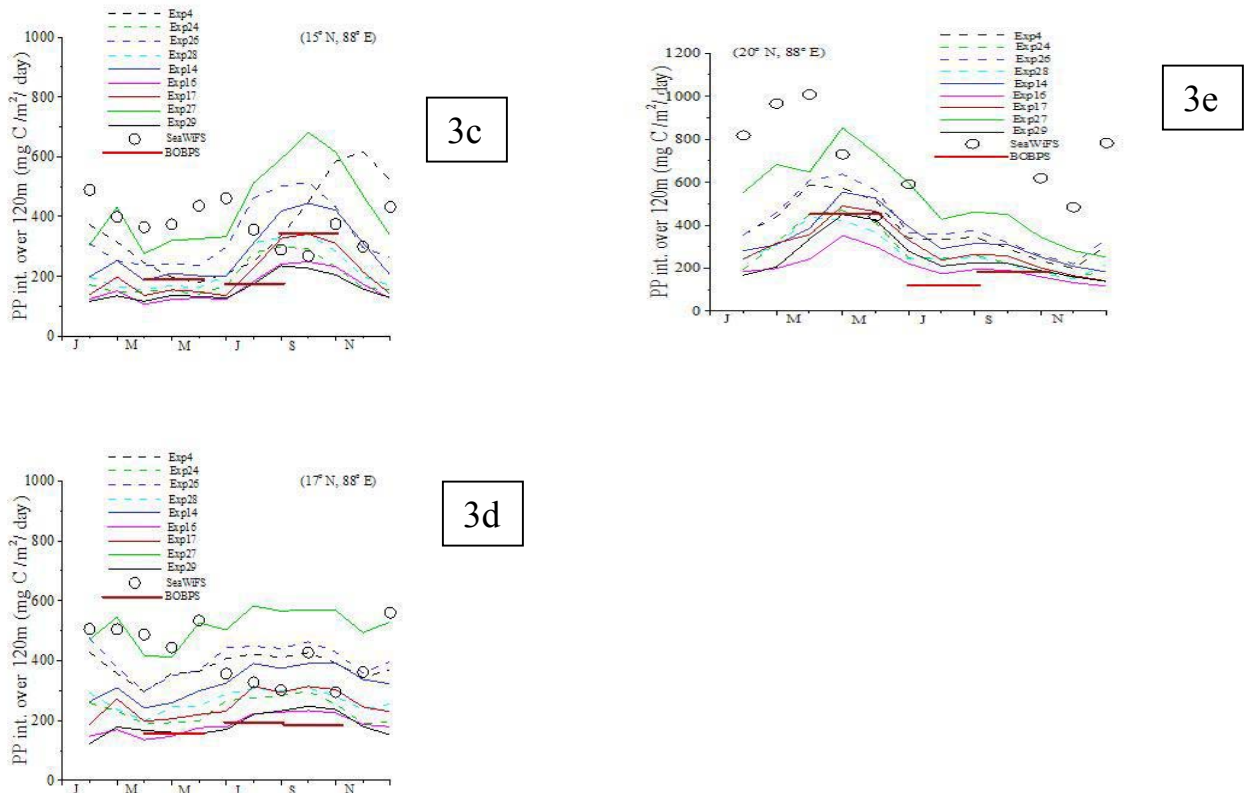
3b

Fig. 3 Seasonal variation of depth integrated PP (mg C/m²/day) at five locations compared with BOBPS and SeaWiFS data

The seasonal variation of depth integrated primary productivity at five stations on the 88° E transect, obtained from nine model simulations are compared with the SeaWiFS data and BOBPS cruise data (fig. 3a, 3b, 3c, 3d and 3e). The model results match well with BOBPS data and SeaWiFS data, in many cases.

In summary, simulation results show that the model primary productivity values agree well with the observed values for many locations and for different experiments during the three seasons, whereas the model chlorophyll values agree well with the observed values at a few locations and that too only for some of the model experiments. In almost all the figures, it can be seen that exp28 seems to fit the chlorophyll best while exp29 fits PP best. Also, it can be observed that the primary productivity values obtained from SeaWiFS data are much different from BOBPS cruise data. It is noted that for making comparisons of model results with the observations, chlorophyll in the model is computed using a constant C:Chl ratio of 50 which may be too simplistic, not realistic, whereas PP is

computed directly in nitrogen units and converted to carbon units using C:N of 7 in the model simulations. In the scientific community, there seems to be better consensus on the C:N ratio than C:Chl ratio.



Fig

Comparison of Results of Basic Experiment, Selected Experiment and Abiotic Model

Based on the comparisons of PP and Chl obtained from model simulations with the observations, and the minimum values obtained for the concentrations of ammonium and zooplankton, a particular experiment (Selected Experiment - exp29) is chosen for detailed analysis of carbon flux across the surface of the ocean. The results obtained from the model experiment, exp29 is compared with the standard numerical experiment results, exp3 and results of abiotic simulation.

The spatial and temporal variation of depth integrated primary productivity and surface chlorophyll obtained from exp29 (Selected Experiment) are shown in Fig.4 and Fig.5 respectively. PP and Chl are less in BOB compared to AS for all the seasons. The basin-wide variation of PP and Chl show that high PP and Chl are seen in North-Western AS and southern coast of India for all the seasons. The basin-wide variation of PP agrees well with the PP data obtained from SeaWiFS (not shown in the figure).

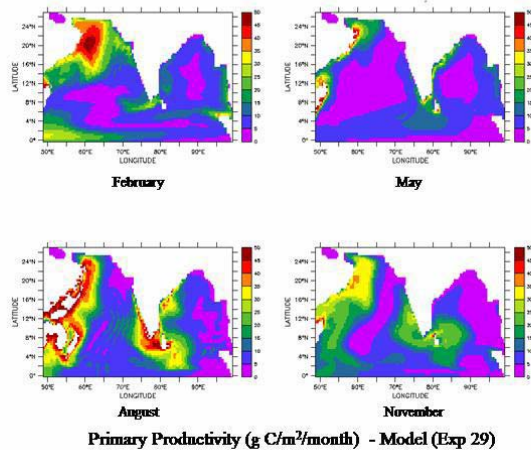


Fig.4 Spatial and temporal variation of depth integrated primary productivity (mg C/m²/day) obtained from model simulation (Selected Experiment - exp29)

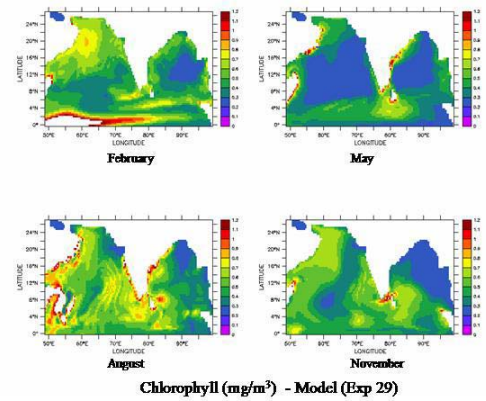


Fig. 5 Spatial and temporal variation of surface chlorophyll (mg Chl/m³) obtained from model simulation (Selected Experiment -exp29)

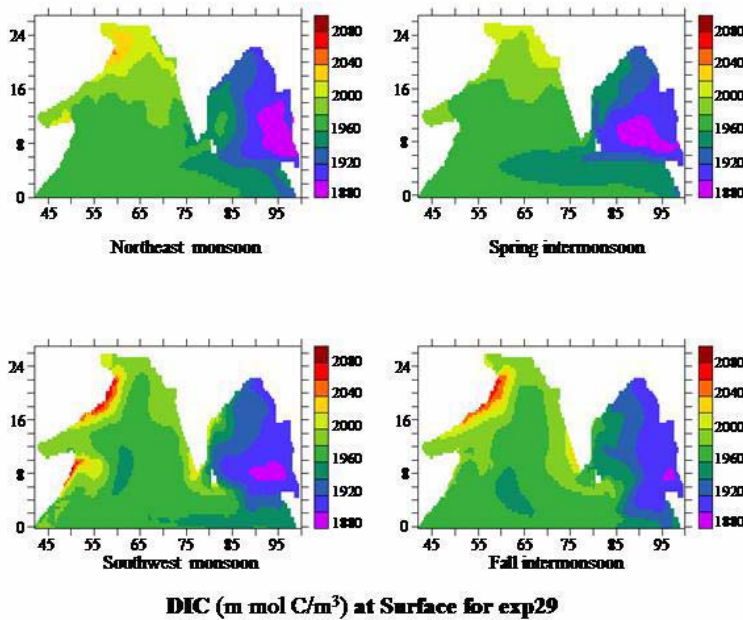


Fig.6 show the spatial and temporal variation of surface DIC for the selected experiment. The spatial and temporal variations of dissolved inorganic carbon (DIC) at the surface and depth averaged values of DIC obtained from the basic and selected numerical experiments, show minimum values in eastern BOB and maximum values close to Oman Coast for all seasons. Also, DIC at surface is less than the depth averaged DIC for both experiments. Surface and depth averaged DIC values for the basic experiment is greater than selected experiment.

F
o
e

Fig.7 show the spatial and temporal variation of surface ALK for the selected experiment. The spatial and temporal variations of alkalinity (ALK) at the surface and depth averaged values of ALK obtained from the basic and selected experiments, show minimum values in eastern BOB and maximum values in the northern AS for all seasons. Surface ALK is slightly less than the depth averaged ALK for both experiments. ALK at surface and the depth averaged value for the basic experiment is slightly greater than the selected experiment. DIC and ALK are less in BOB compared to AS for all the seasons in both experiments.

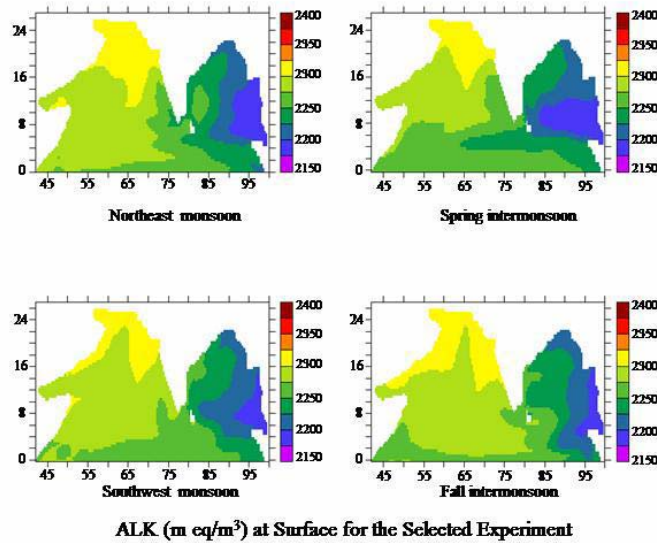
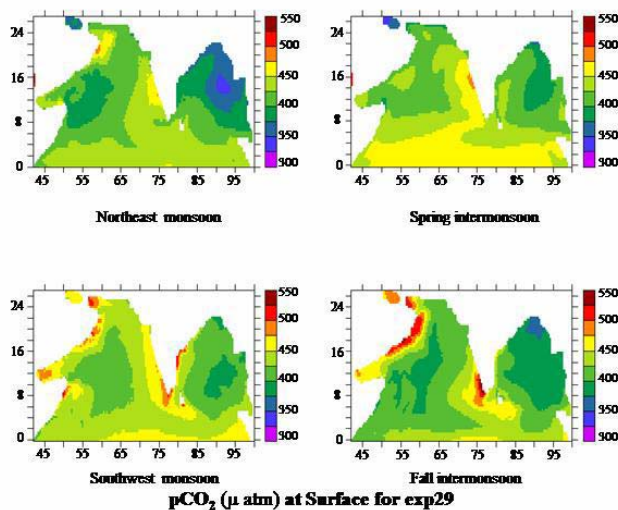


Fig.7 Spatial and temporal variation of ALK (m eq/m³) obt from model simulation (Selected Experiment -exp29) at surf



The spatial and temporal variation of pCO₂ shows that pCO₂ in BOB is lower than in AS. Minimum values of pCO₂ are seen in central and eastern BOB and maximum values are seen close to the Oman coast and the west & east coast of India for both experiments and all seasons. Minimum values of pCO₂ are obtained in the central and eastern Bay during NEM. It is seen that pCO₂ for the selected experiment is much less than basic experiment (fig. 8).

patial and temporal variation of pCO₂ (m atm) obtained from

Spatial and temporal variation of carbon flux (cfl) across the surface of the ocean shows that cfl in BOB is less than AS. The simulation results show minimum cfl in central and eastern BOB and maximum cfl close to Oman coast and west & east coast of India for all seasons and for both experiments. Higher values of cfl are obtained during SWM in AS and BOB for both experiments compared to other seasons. Maximum values of cfl are seen during SWM close to Oman and Somali coast. Drawdown of carbon at the surface is seen at eastern BOB during NEM for the selected experiment (fig. 9). The values of cfl for the selected experiment are much lower than the basic experiment for all seasons both in AS and BOB.

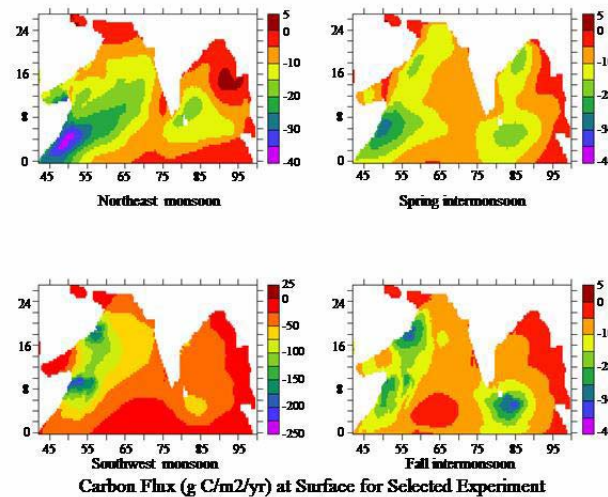


Fig. 9 Spatial and temporal variation of surface Carbon flux ($\text{g C/m}^2/\text{year}$) from atmosphere to ocean obtained from model simulation (Selected Experiment -exp29)

The spatial and temporal variation of Carbon flux obtained from the simulations is compared with the climatological data set of carbon fluxes of Takahashi et al. Carbon flux is less in BOB compared to AS during all seasons. Values of carbon flux are higher during SWM and FIM. Maximum values of carbon flux are seen close to Oman Coast during SWM and FIM, close to Somali Coast during NEM. Drawdown of carbon is seen in Northern BOB during NEM and Eastern BOB during FIM.

Role of Biology in Carbon Cycle

The results of the abiotic and biotic simulations for both experiments (basic and selected) are compared. Spatial and temporal variation of difference in pCO_2 for the selected experiment and abiotic simulations show that pCO_2 in biotic case is less than abiotic case in the northwestern AS, west, east and southern coast of India (all regions of significant productivity). pCO_2 for biotic is slightly more than that of abiotic in the central AS for all seasons, and whole of BOB during SIM, SWM, and eastern BOB during NEM and FIM. Maximum difference is seen near the Oman coast.

Spatial and temporal variation of difference in carbon flux from the surface of the ocean (cfl) to atmosphere for the selected experiment and abiotic simulations show that cfl is less for biotic case than the abiotic case in the regions of significant productivity i.e., northwestern AS, west, east and southern coast of India for all seasons. The values of cfl for the biotic case are slightly greater than the abiotic case in the central AS and whole of BOB for all the seasons. Maximum

differences are seen near the Oman coast.

Latitudinal variation of the surface pCO₂ in biotic (Physical-Biological-Chemical model) and abiotic (Physical-Chemical model) simulations for the 88° E (BOB) and 65° E (AS), for July to October shows Surface pCO₂ is lower in the biotic simulations compared to abiotic simulations, during July to October almost everywhere in AS, but pCO₂ is slightly more in the biotic simulations than abiotic simulations in BOB. Also, pCO₂ is more in AS than in BOB except in a small equatorial region in the BOB. Furthermore, the surface pCO₂ is always greater than the atmospheric pCO₂ (360 matm). Therefore, ocean is outgassing at all locations on 88° E and 65° E transects in both abiotic and biotic simulations during July to October.

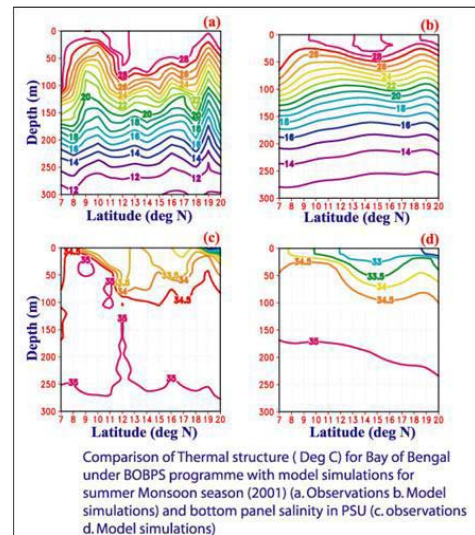
The contribution of the biological pump in north Indian Ocean (above the equator), AS (west of 75°E) and BOB (east of 75°E) in the annual carbon budget is given in Table 2, where carbon flux from the ocean to the atmosphere indicates the magnitude of outgassing over a year. While the biological pump decreases outgassing by 20% in AS, it increases in BOB by 12%, the absolute magnitude of the effect being much smaller in BOB than AS. The effect of the biological pump over the entire north Indian Ocean on a year is decrease of outgassing by 13%. The preceding discussion explains that this rather unexpected effect is due to dominance of regeneration over carbon fixation in large parts of the north Indian Ocean. It is also noteworthy that the carbon flux in AS is nearly two and half times that in BOB.

Physical Model Simulations using NCEP data

Under BOBPS programme, NIO Goa has collected physical parameters for 3 different seasons - summer monsoon (6th July-2nd August 2001), Fall intermonsoon (14th September-12th October 2002) and Spring intermonsoon (12th April-7th May 2003). The observations were taken on board ORV Sagar Kanya. There were 14 CTD stations in the open Bay of Bengal, at 1° interval. Some of the physical parameters measured in these cruise observations are profiles of temperature, salinity upto a depth of 1000m using the CTD's. Wind speed and direction and current speeds were also measured using automatic weather stations and ship board ADCP respectively. Details of the cruise data and their results can be seen in Prasanna Kumar et al. (2004).

Initially, results of climatological simulations were compared with observations to see how far the model is able to simulate the thermal structure and salinity. Since, the climatological runs could not capture the sharp gradients seen in the observations for physical parameters, 6-hourly wind forcing is used to simulate the small scale features seen in the observations.

Fig.10 shows the comparison of the vertical section of temperature (deg C) obtained from observations (Fig. 10a) with the results of model simulations (Fig. 10b) for the 2001 summer



monsoon. The thermocline in the model is quite close to that of observations. The sea surface temperature obtained from the model simulations is around 29°C along the 88°E longitude and 7-20°N latitude transect. Oscillations in the top 300m of thermal structure in the thermocline region, and upheaval of isotherms are noticed between 7-10°N in the simulations. Also, shoaling towards 10°N and 19°N is seen in the simulation results. These two upheavals are the indications for the signature of subsurface cold-core eddies (Prasanna Kumar et al., 2004). In the model simulations, the eddy is not expected to be captured very well, but smoothed signature is present at 9°N and 18°N.

During 2002, thermocline oscillations are observed in the top 300 m depth along the open ocean transect. The isotherms shows shoaling at 7°N and extended till 9°N, then deepened towards 11°N. Even the model simulated thermocline also shows these oscillations along the open ocean transect. The thermocline in the top 100m shows a northward shoaling. During 2003, the observations show very sharp gradient in the isotherms between 18°-20°N latitude and in the top 100 m between 7°-13°N. The model simulations are not able to capture well the thermal structure variations which were observed during 2003.

The temperature profiles obtained from model simulations are compared with observations for stations along the 88°E. The rms error is ranging from 0.8035 to 2.874 in 2001. In most of the places the model derived temperature is in close agreement with observations, but there are some deviations at few locations.

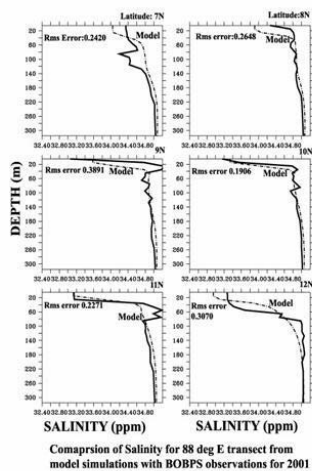


Fig. 11 Comparison of salinity structure for 88°E transect from model simulation with BOBPS observations at various latitudes for 2001

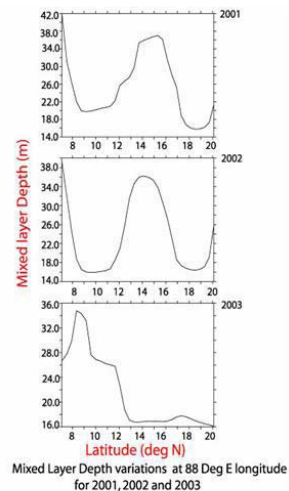
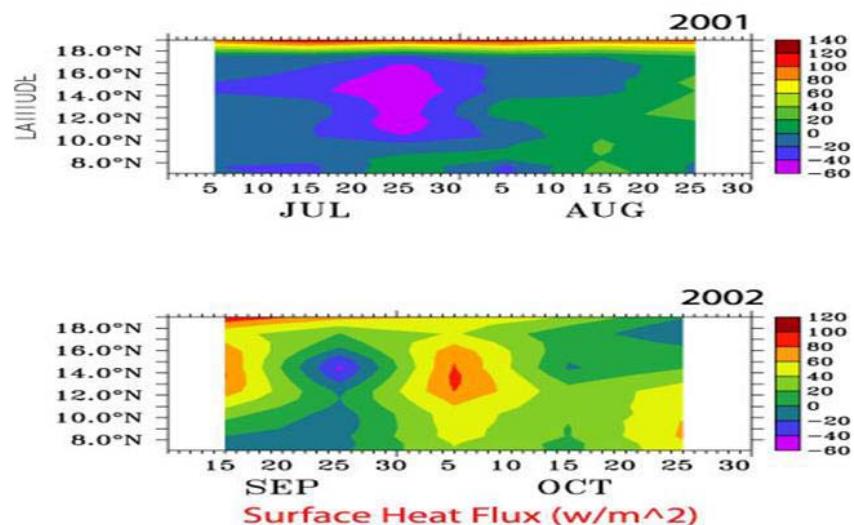


Fig. 12 Mixed layer depth (m) derived from Model simulations for (a) Summer monsoon season of 2001 (b) Fall termonsoon season of 2002.

Salinity structure simulated from the model (Fig.10c,d) is not able to capture the sharp gradient seen in the observations (Fig.10c). During 2001, salinity variations are observed in the top 75 m and salinity decreases towards north. Below 75m, the presence of homogeneous waters are indicated by uniform salinity. In 2002, the vertical salinity structure along the open ocean transect showed a strong gradient in the upper 50 m in the observations which has been simulated even in the model simulations. The salinity of 34.5 psu is observed in the top 40 m at 7°N, and increased towards north. This indicates the fresh water input from various sources like river run-off and oceanic precipitation (Prasannakumar et al., 2002). The model simulations are also able to capture the trend, but the sharp gradients are not present. Similarly in 2003 there are salinity variations in the top 100 m ranging from 32.5 to 34.5 psu in the observations. These variations are also seen in the model simulations. The rms error for the year 2001 ranges from 0.1906 to 0.9788, the model is having good correlation in the open ocean rather than along the coast (Fig. 11).

Mixed layer depth from the simulations is determined as the depth at which the surface temperature differs by 0.2 deg from the surface temperature. It is noted that the model is able to pick up the deepening and shallowing in the various seasons, though there are quantitative differences from the observations (Fig. 12). In 2001, a steady increase towards north, deepening upto 40 m at 11°N and shoaling of mixed layer depth from 11°N to 20°N are obtained from the model simulations. In 2002 also similar variations are seen, but in 2003 the mld has maximum deepening at 8 deg N. The model is able to pick up the deepening and shallowing in the various seasons, though there are quantitative differences from the observations. It is also noted from the model results that the surface heat fluxes are negative in the summer monsoon season and positive during the Fall intermonsoon season (Fig. 13).



at fluxes for (a) Summer monsoon season of 2001 (b) Fall intermonsoon season of 2002.

During 2001, model simulations show the strong eastward currents in the eddy region between 7°-10° N (maximum speed of 45 cm/s), but are less compared to the observed velocities, in the top 150 m (Prasannakumar et al., 2004). Between 10°-13° N weak westward currents are seen (< 5 cm/s). In 2002 the zonal currents are of the speed 45 cm/sec between 7-10N and are eastward, and between 10°-13°N westward currents of low speeds are seen in the model. During April - May of 2003 which is a transition period weak westward currents are obtained from model between 7-10°N.

Conclusions

A new formulation for uptake of nutrients (YS) in a multi-nutrient environment was proposed with similarity and hyperbolicity taken as basic properties. This formulation was applied to the nitrate-ammonium environment in the Arabian Sea, and was found to agree well with the recent observations. Six different formulations for nitrate uptake were incorporated in the mixed layer model of marine ecosystem (FDM model) and chlorophyll values from the model were compared with SeaWiFS data at a few locations in AS and BOB, and it was found that chlorophyll obtained from YS agrees well with the observations.

The simulations were carried out for three dimensional coupled physical-biological (FDM) model for three different formulations of nutrient uptake (WR, ON & YS). The spatial variation of annual primary productivity for YS relation compared well with the SeaWiFS data. The profiles of chlorophyll, primary productivity and nitrate from the simulation with YS relation, at a location in AS matched well with the US JGOFS data.

Several numerical experiments for the coupled physical-biological and physical-biological-chemical model were carried out using the YS relation for nitrate uptake and by varying the parameters influencing the zooplankton grazing and regeneration of ammonium by zooplankton and bacteria.

Detailed analysis of fluxes and concentrations of tracers was carried out for two numerical experiments, namely, basic experiment (standard set of parameter values) and a particular numerical experiment (selected experiment) which yielded the minimum zooplankton and ammonium concentration. The spatial variation of primary productivity in the euphotic zone and surface chlorophyll agrees well with the SeaWiFS data except in regions of freshwater input from rivers, for all seasons. The latitudinal variation of depth integrated values of PP for three seasons on 88° E transect from the selected experiment compares well with cruise data of BOBPS and SeaWiFS data, but the depth integrated values of chlorophyll obtained from selected experiment are always much greater than that of the cruise data.

Chl, PP, DIC, ALK, pCO₂ in BOB are found to be less than those in AS for both numerical experiments. Hence the carbon flux from ocean to atmosphere is lower in BOB. The net effect of the biological pump is to decrease outgassing in AS by about 20% and to increase it in BOB by about 12%. Our results on spatial variability of seasonal carbon flux are broadly similar to those of Takahashi et al (1999), keeping in mind the differences due to resolution. pCO₂ at the surface from the model simulations is comparable with the values available from the BOBPS cruise for one season.

The simulation results of the selected experiment show that biology reduces the outgassing. AS and BOB are sources of carbon for both biotic and abiotic experiments during all seasons.

Abiotic carbon flux from ocean to atmosphere is less than biotic for the basic experiment and abiotic carbon flux from ocean to atmosphere is more than biotic for the selected experiment at regions where primary productivity is high. These numerical experiments carried out using different sets of parameter values show that the estimate of carbon flux across the surface of the ocean is influenced to a great extent by the parameter values used for simulations.

In the modified physical simulations, NCEP 6-hourly winds are used instead of climatological forcing. This forcing is able to capture eddy like features which are seen in the observations. To simulate the salinity structure better in the Bay of Bengal it is required to include freshwater flux as one of the forcings.

It is planned to carry out three dimensional coupled (physical-biological-chemical) model simulations using the real-time forcing to get more realistic results on concentrations of state variables and fluxes.

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Table 1 Parameter values used in present numerical experiments
In the text, exp3 is Basic Experiment, **exp29** is Selected Experiment

Exp. No.	k3	g	m5	g3	g4
p14	1	0.75	0.05	0.75	0.33
exp16	1	1	0.05	0.5	0.33
exp27	0.6	0.6	0.05	0.75	0.33
exp28	1	1	0.033	0.75	0.5

0.058	0.065	12.1	0.0135
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9. Atmospheric aerosols study

Participants:

Physical Research Laboratory, Ahmedabad

M.M. Sarin **Principal Investigator**
A.K. Sudheer
Lokesh Sahu

Objective

To study the chemical characteristics of aerosols and their deposition fluxes over the Bay of Bengal.

Introduction

The marine aerosol particles play an important role on global geochemical cycling processes. The major constituents of marine aerosols are derived from two principal sources: The long range transport of continentally derived aerosols of natural and anthropogenic origin and those resulting from the sea salt sprays. Recent studies have shown that the episodic inputs of chemical species such as nitrogen via aerosol deposition may have a significant influence on the marine biological productivity (Duce *et al.* 1991, Owens *et al.* 1992). Likewise, long range transport of sulphate from the continents can have a major impact on the marine environment (Tarasson *et al.* 1995). As a part of the India (JGOFS) programme, we have studied the atmospheric inputs of nitrate (NO₃) and non-sea-salt sulphate (nss-SO₄) to the surface Arabian Sea (Sarin *et al.* 1997). We have used ²¹⁰Pb as a tracer to delineate the sources and deposition fluxes of these constituents over the Arabian Sea. A seasonal pattern is clearly evident, with increasing concentrations of NO₃, nss-SO₄ and ²¹⁰Pb occurring in the winter months, suggesting their continental source. Our study shows that for a high productive oceanic region such as northern Arabian Sea, the atmospheric supply of NO₃ to the euphotic zone is insignificant compared to that supplied from deep water upwelling (Sarin *et al.* 1994b).

Methods

High-volume bulk-aerosol samples were collected in the near surface marine boundary layer (MBL) of Bay of Bengal, on board ORV Sagar Kanya Cruise (No.161), along a transect from 20°N 89°E to 4°N 84°E during 18 Feb. – 8 March 2001. Bulk-aerosols were collected with a high-volume (1.2 m³ min⁻¹) air sampler set up ~20m above the sea surface on the upper deck of ORV Sagar Kanya. Air was filtered through 20x25 cm size Pallflex Tissuequartz filters while cruising along the sampling tracks. Typically, aerosol samples were collected for 10-20 hr duration and the volume of air-filtered ranged from 700 to 1900 m³. The samples were analyzed for water-soluble ionic species (NH₄⁺, Na⁺, K⁺, Mg²⁺, Ca²⁺, Cl⁻, NO₃⁻ and SO₄⁼), trace metals (Al, Fe, Ca, Mg, Mn, Zn, Cu, Ni) and Be-7 (477 keV) and Pb-210 (46.5 keV) activities.

Results

On average, SO₄⁼ is the dominant constituent of aerosols (range : 2.4 to 7.7. μg m⁻³) and accounts for nearly 60% of the total water-soluble species. The pronounced non-sea-salt (nss) components of K⁺ (60-99%), Ca⁺⁺ (36-99%), Mg⁺⁺ (5-80%) and SO₄⁼ (73-99%) indicate that meteorological conditions favouring the transport of anthropogenic emissions dominate the aerosol composition in the MBL of Bay of Bengal. The NH₄⁺ concentration ranges from 0.2 to 1 μg m⁻³ and NO₃⁻ levels are generally less than 1 μg m⁻³. Furthermore, significant statistical correlations between nss-Ca⁺⁺, nss-Mg⁺⁺, and nss-SO₄⁼ document the long-range transport of

biogenic emissions and crustal-dust from the arid regions of South Asia (Fig. 1). The impact of enhanced levels of nss-SO_4^- found in all samples (range: 2.3 to $7.4 \mu\text{g m}^{-3}$) is conspicuously reflected in the widespread depletion of chloride (55-98%) from sea-salt particles. Relatively large chloride deficit is associated with smaller size particles and strongly correlated with nss-SO_4^- , suggesting that sea-salts are a potential sink for anthropogenic SO_2 . This potential sink has significant implications for the chemistry of other trace gases, including ozone, whose atmospheric cycle is influenced by NO_x and SO_2 . It is noteworthy that scatterplot for nss-SO_4^- versus O_3 at all the sites over Bay of Bengal shows statistically significant correlation, reflecting their dominance from anthropogenic sources.

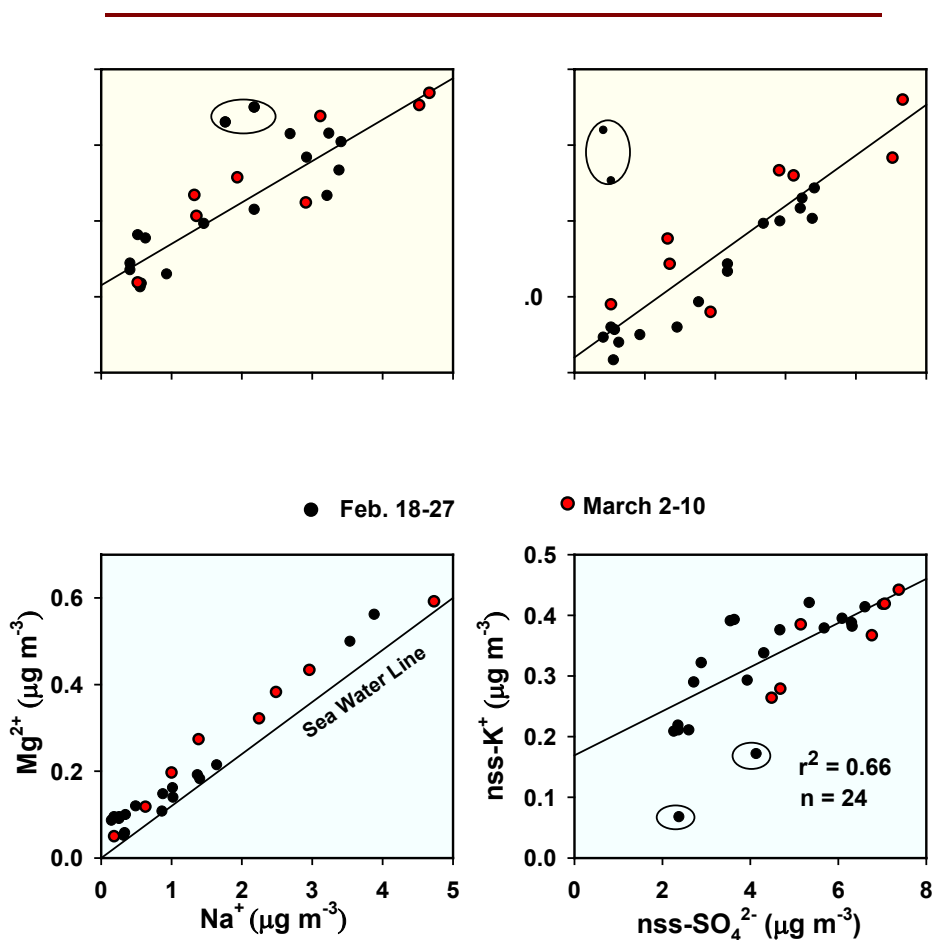


Fig. 1 Relationship among water soluble ionic species in the aerosol

In general, concentrations of Al ($309\text{--}1865\text{ ng m}^{-3}$), Fe ($326\text{--}2488\text{ ng m}^{-3}$), Ca ($69\text{--}1030\text{ ng m}^{-3}$), Mg ($43\text{--}983\text{ ng m}^{-3}$) and Mn ($2\text{--}38\text{ ng m}^{-3}$) were higher at sampling sites in the eastern Arabian Sea compared to those in the Bay of Bengal (Al: $40\text{--}645$, Fe: $40\text{--}807$, Ca: $21\text{--}185$, Mg: $5\text{--}119$, Mn: $0.8\text{--}7\text{ ng m}^{-3}$), suggesting the relative dominance of dust sources over the Arabian Sea (Fig.2).

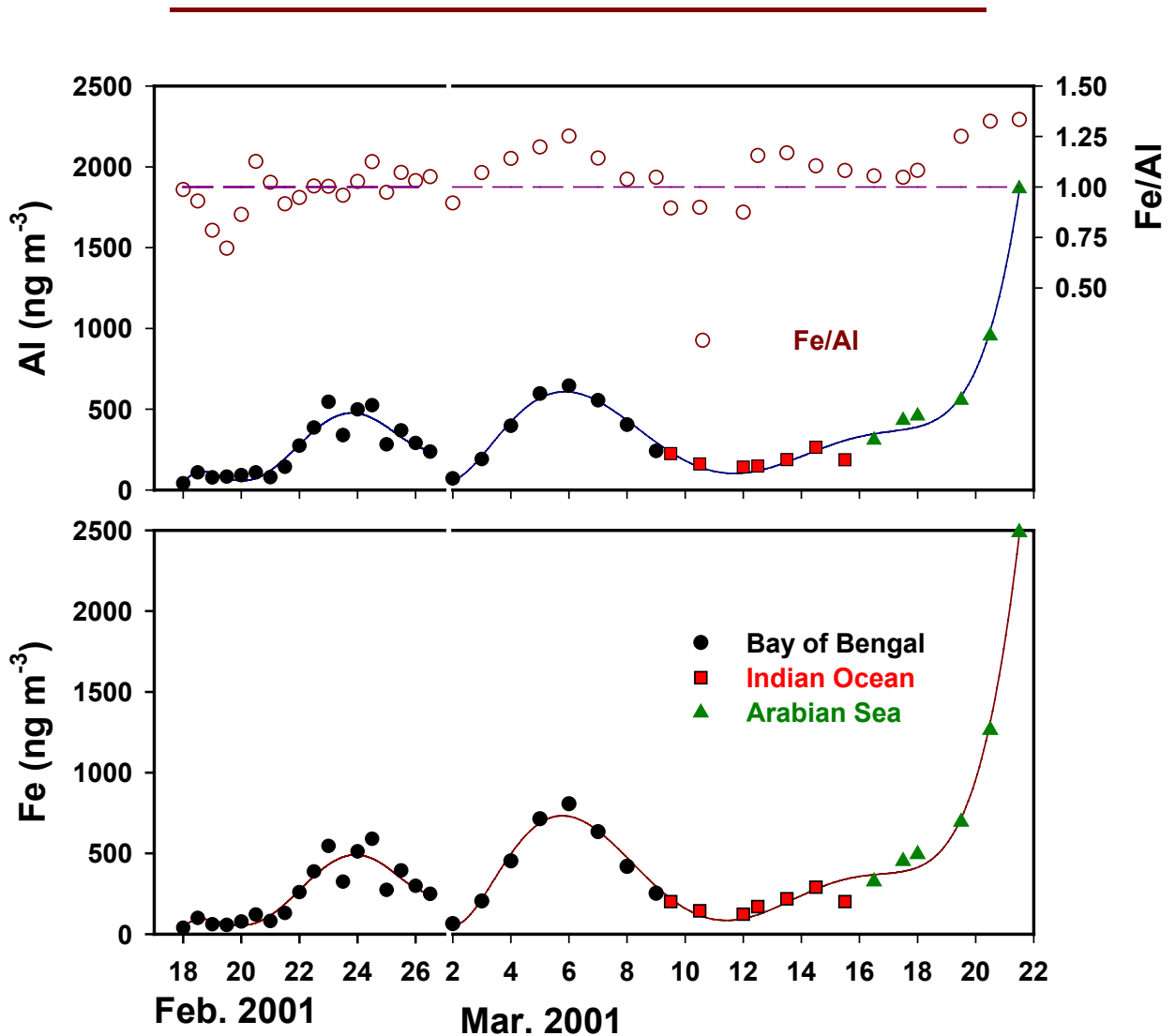


Fig. 2 Spatial and temporal variability in Fe and Al concentrations over the Bay of Bengal, northern Indian Ocean and Arabian Sea.

In comparison, concentrations over the northern Indian Ocean were lowest among the three oceanic regions. Significant correlations have been found among Al, Fe, Ca, Mg, Mn for all the sampling sites, suggesting a common crustal source and transport process for these aerosol constituents.

Aerosol Be-7 concentrations in the surface air over the Bay of Bengal ranged from 2.7 to 7.4 mBq m^{-3} ($A_v = 5\text{ mBq m}^{-3}$) and those of Pb-210 varied from 1.1 to 1.8 mBq m^{-3} ($A_v = 1.3\text{ mBq m}^{-3}$).

m^{-3}). There are no pronounced latitudinal variations found in the aerial distribution of Be-7 and Pb-210. However temporal variation in the data is somewhat discernible. Be-7 concentrations during the sampling period of 2-8 March 2001 are consistently higher than those measured during 18-23 Feb. 2001 (Fig. 3); an observation consistent with higher aerosol loading of the atmosphere during early March.

Spatial and temporal variations: ^7Be & ^{210}Pb

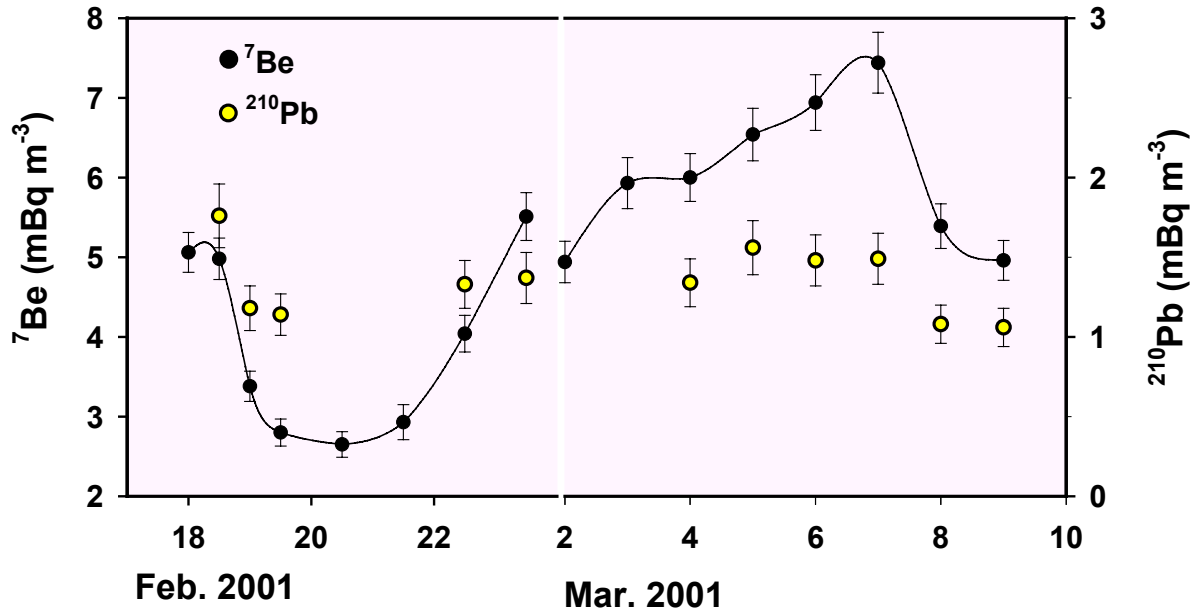


Fig.3 Spatio-temporal variability of Be-7 and Pb-210 in the Bay of Bengal

The variations in Be-7/Pb-210 ratios are useful to determine whether the source of a scavenged air mass is oceanic versus continental and/or upper versus lower tropospheric. The Be-7/Pb-210 ratios over the Bay of Bengal ranged from 2.4 to 5.0; with consistently higher ratios (4.2 to 5.0) along the southern transect (15°N 87°E to 4°N 84°E). It is noteworthy that relatively higher Be-7 concentrations over the northern Indian Ocean and eastern Arabian Sea during the time period of 9-22 March 2001 are similar to those over the Bay of Bengal. This is presumably due to relatively higher stratospheric intrusion and descending air from the upper troposphere.

10. Summary and Conclusions

New insight emerging out of the BOBPS data are the following:

1. Extremely shallow and time-invariant/weakly varying mixed-layer in the northern Bay of Bengal is due to the excess freshwater, which remains through out the year.
2. The semi-annual variability of mixed-layer depth in the southern Bay of Bengal the is regulated by a combination of atmospheric forcing (heat and buoyancy flux), advection of high salinity Arabian Sea water into the Bay, and the propagation of Rossby waves.
3. The low chlorophyll and biological productivity in the Bay of Bengal is due to the strong stratification primarily driven by the presence of fresh water which inhibits wind-driven vertical mixing and upward supply of nutrients from subsurface.
4. Subsurface chlorophyll maxima is observed throughout the year and deepest occurs in wintertime.
5. The shallow euphotic depth in the northern Bay during summer and fall intermonsoon, due to suspended sediment load, is not conducive for higher column primary productivity.
6. Cold-core eddies enhance the biological productivity in the Bay of Bengal by eddy-pumping which enables the vertical transfer of nutrients across the halocline.
7. Mesozooplankton biomass appears to be decoupled with chlorophyll and primary production.
8. Bacteria abound, which is far more than those in the AS, appear very crucial for microheterotrophs in southern and open-ocean regions of the Bay.
9. N^{15} based measurements indicate that Bay may be capable of supporting high new production.
10. The Rapid decrease of the amino acids, amino sugars and carbohydrates, which were found to be the important constituents of the suspended particulate matter and the sediments, clearly suggested that these compounds were quickly mineralized in water column.
11. Contrary to the earlier belief that the Bay of Bengal may be a sink for CO_2 , the pCO_2 and TCO_2 measurements indicate that except in the northern Bay of Bengal during summer and fall intermonsoon Bay of Bengal is a minor source of CO_2 to atmosphere.

11. Papers published

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13. Jayu Narvekar and Prasanna Kumar, S. Seasonal variability of the mixed layer in the central Bay of Bengal and associated changes in nutrients and chlorophyll, **Deep-Sea Res. I**, 53, 820-835, **2006**.

List of Manuscripts under preparation/Submitted

1. Nuncio, M and S. Prasanna Kumar, Eddies associated with the seasonal western boundary current in the Bay of Bengal, **Journal of Geophysical Research** (Submitted).
2. Sugandha Sardessai, N. Ramaiah, S. Prasanna Kumar and S. N. de Sousa, Seasonal variability of dissolved oxygen and nutrients in the Bay of Bengal, **Journal of Marine Research** (Submitted).
3. Prasanna Kumar, S., M. Nuncio, N. Ramaiah, S. Sardesai, Jayu Narvekar, Veronica Fernandes, Jane T. Paul, Eddy mediated biological productivity in the Bay of Bengal during fall and spring intermonsoons, **Deep Sea-Research I** (Under preparation).
4. Veronica Fernandes, N. Ramaiah, Jane T. Paul and S. Sardesai, Spatial variations in bacterioplankton abundance and production in the Bay of Bengal during the 2002 postmonsoon, **Journal of Sea Research** (Submitted).
5. Jane T. Paul, N. Ramaiah, Veronica Fernandes and Avina Baretto. Distribution and Abundance of Phytoplankton Assemblages in the Central Indian Ocean, **Botanica Marina** (Submitted).
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