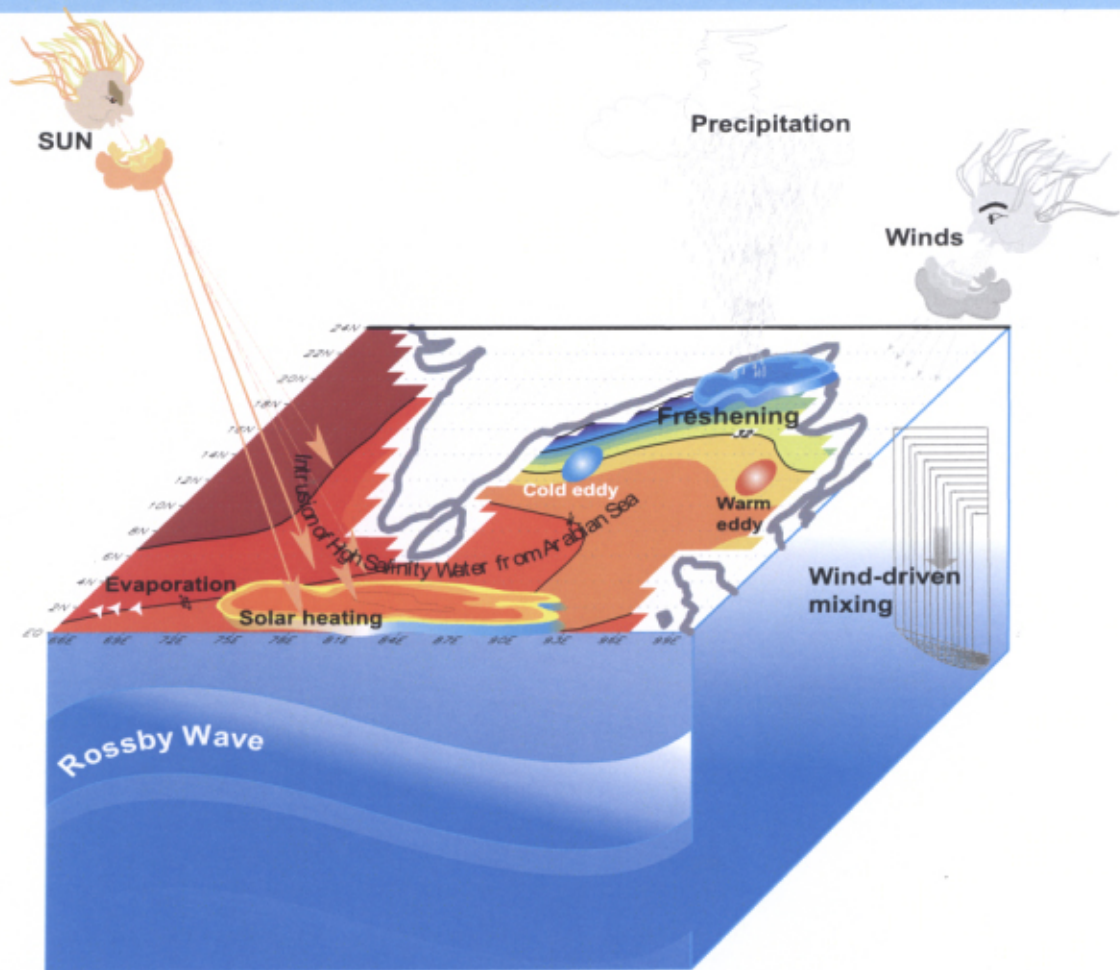


# Seasonal Variability of the Upper Ocean Driven by the Atmospheric Forcing and its Regulation of Nutrients and Chlorophyll in the Bay of Bengal

Thesis submitted to  
**Goa University**  
For the degree of  
**Doctor of Philosophy**  
in  
**Marine Sciences**



by  
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**National Institute of Oceanography,**  
*Goa, India.*

**August 2008**

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## Statement

As required under the University ordinance 0.19.8(vi), I state that this thesis entitled “Seasonal variability of the upper ocean driven by the atmospheric forcing and its regulation of nutrients and chlorophyll in the Bay of Bengal” is my original contribution and it has not been submitted on any previous occasion.

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

Jayu Narvekar

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# Certificate

This is to certify that the thesis entitled “Seasonal variability of the upper ocean driven by the atmospheric forcing and its regulation of nutrients and chlorophyll in the Bay of Bengal” submitted by Ms. Jayu Narvekar for the award of the degree of Doctor of Philosophy in Marine Science is based on original studies carried out by her under my supervision. The thesis or any part thereof has not been previously submitted for any other degree or diploma in any institution.

Dr. S. Prasanna Kumar

Research Supervisor

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Dona Paula, Goa

Place: Dona Paula

Date:

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*Guru Brahma Guru Vishnu Guru Devo Maheshwarah |*

*Guru Saakshaat Par-Brahma Tasmai Shree Gurave Namah ||*

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## Abstract

The upper ocean is the most variable and dynamically active part of the marine environment that couples the underlying ocean to the atmosphere above through the transfer of mass, momentum and energy. The thickness of mixed layer is an important parameter in determining the quantity of heat that is available for exchange with atmosphere which is capable of triggering several ocean-atmosphere coupled processes. Mixed layer also plays an important role in determining the chlorophyll biomass and biological productivity of the upper ocean. The present thesis is an attempt to decipher the basin-scale variability of the mixed layer in the Bay of Bengal on a seasonal scale and the factors responsible for it. The aim is also to understand how the changes in water column nitrate and chlorophyll are linked to the upper ocean variability.

A suite of *in situ* as well as remote sensing data was used. The *in situ* data consisted of temperature, salinity, nitrate and chlorophyll *a* profiles derived from World Ocean Data Base and Responsible National Oceanographic Data Centre (RNO DC) at National Institute of Oceanography, which archives the data collected by Indian research ships. In addition temperature and salinity profiles from Argo were also used. These data were used to prepare the monthly mean temperature and salinity climatology, while seasonal climatology was prepared for nitrate and chlorophyll *a* on a  $1^{\circ}\times 1^{\circ}$  spatial grid. In addition to this, the high resolution *in situ* data collected during Bay of Bengal Process Studies (BOBPS) during summer (6 July to 2 August, 2001), fall intermonsoon (14 September to 12 October, 2002), spring intermonsoon (12 April to 7 May, 2003), and winter (25

November 2005 to 4 January 2006) were also utilized to delineate the effect of meso-scale variability on mixed layer depth.

As the salinity changed rapidly in the upper layers in the Bay of Bengal due to freshening by river runoff as well as precipitation, density criteria was used to define mixed layer for the present study. Mixed layer was defined as the depth at which the density ( $\sigma_t$ ) exceeds  $0.2 \text{ kg m}^{-3}$  from its surface value. The barrier layer was numerically calculated by subtracting the mixed layer depth (MLD) from the isothermal layer. The isothermal layer for the present study was defined as the depth at which the temperature decreased by  $1^\circ\text{C}$  from its surface value.

The atmospheric data used was monthly mean climatology of the incoming short wave radiation, wind speed, evaporation, precipitation and net heat flux on  $1^\circ \times 1^\circ$  grid, which was obtained from National Oceanographic Centre (NOC), Southampton for the period 1980-1993. The remote sensing data used for the study was the chlorophyll pigment concentrations from SeaWiFS during the period September 1997 to December 2007 and the merged sea-level anomalies of Topex/Poseidon ERS1/2 series of satellites obtained from AVISO live access server during the period October 1992 to January 2006. From the sea-level height anomalies, velocities were computed assuming geostrophic balance.

The mixed layer and barrier layer variability were examined in the light of heat flux, momentum flux (wind-stress curl) and fresh water flux (evaporation-precipitation) to decipher the factors that are responsible for their changes.

The mixed layer depth (MLD) during the spring intermonsoon (March-April-May) was the shallowest in the Bay of Bengal compared to the rest of the season. It varied between 10 and 25 m in March and April. This shallow MLD was driven by the strong stratification induced by peak solar heating (280-290 W/m<sup>2</sup>) and subsequent highest net heat gain by the ocean (150-160 W/m<sup>2</sup>). The low salinity waters (< 32.5 psu) in the northern Bay (north of 18°N) during March-April made the upper ocean highly stratified. The weak winds during this period were unable to drive deep wind-mixing due to strong stratification and hence resulted in the formation of shallow mixed layer.

In the south, the comparatively deeper mixed layer (~ 35 m) seen west of 90°E was due to the presence of high salinity waters (>34.5 psu) which made the water column less stable and the moderate winds were able to initiate greater mixing leading to the observed deep MLD. However, the deep MLD east of Sri Lanka was linked to the development of anti-cyclonic circulation associated with the formation of subtropical gyre which begins in May. This anti-cyclonic circulation drives down-welling and deepens the mixed layer. The co-location of comparatively deep MLD (>25 m) and strong negative wind stress curl (~ -20 x 10<sup>-8</sup> Pascal/m) along the western boundary in April suggested the role of wind stress curl in deepening the mixed layer. Note that the subtropical gyre was well developed in April in the central and western Bay of Bengal, which also leads to down-welling and augments the deepening of the mixed layer. The deep MLD in May in the south, south of 4°N, was related to the downward Ekman pumping due to the negative wind stress curl. In addition to this the time-longitude plot of sea-level height anomaly along 4°N showed the propagation of Rossby waves during spring intermonsoon, which also contributed in deepening the mixed layer.

During summer monsoon (June-July-August) though the wind speed was the highest in the entire basin, the MLD was the shallowest in the northern Bay (~ 5m). An examination of E-P showed that it was negative and the highest of all the season, implying excess precipitation (in excess of 440 mm/month), in the northern Bay. In addition to the oceanic precipitation, the influx of freshwaters from the rivers adjoining the Bay of Bengal also contributed towards freshening of the surface waters of the Bay. The spreading of low salinity waters (<32 psu) were seen from the northern Bay towards the south and east with the progress of summer monsoon. The vertical profiles of stability parameter showed that these low salinity waters strongly stratified the upper ocean. The warm upper ocean with SST in excess of 28.5°C also contributed towards strengthening the stratification. Hence, the winds though were the strongest of all the season, were unable to break the stratification to initiate wind-driven mixing and deepen the mixed layer. The shallow MLD seen around Sri Lanka was driven by the positive wind stress curl. The positive wind stress curl was seen developing in May, which peaked in June and collapsed by September. The upwelling associated with the positive wind stress curl drives an upward Ekman pumping and this led to the observed shallow mixed layer during summer monsoon. The band of deep mixed layer seen extending from the southwestern region into the central Bay was linked to the advection of high salinity waters from the Arabian Sea. This high salinity waters reduced the stratification of the upper ocean as could be inferred from the stability parameter. Thus, the strong winds of the summer monsoon combined with the less stratified upper ocean in the southern Bay due to the intrusion of high salinity waters from the Arabian Sea were able to drive strong wind-driven mixing. This was the mechanism which led to the formation of deep MLD in

the south. In addition to this, the high sea-level anomaly in the central and eastern part of the southern Bay associated with the propagating Rossby waves also contributed towards deep MLD.

As the summer monsoon tapers off and the fall intermonsoon (September-October) sets in, the shallow MLD which was confined to northern Bay, north of 18°N, was seen extending southward to 15°N in October. This could be explained in the context of changing atmospheric forcing from summer monsoon to fall intermonsoon. The short wave radiation as well as net heat flux showed a secondary heating of the upper ocean during fall intermonsoon and accordingly the SST was in excess of 29°C in October. Though the E-P showed a rapidly decreasing precipitation, the surface salinity showed a progressive decrease from that of summer monsoon and also a further southward extension of the low salinity waters. This indicated that the shallow MLD in the northern Bay and its further southward extension was linked to the presence of low salinity waters and its advection southward. The winds over the Bay showed a drastic reduction in their speed in the north during fall intermonsoon with the high wind speed confined to the southern Bay. Thus, the deep MLD in the southern Bay was driven by a combination of comparatively high wind speed and the presence of high salinity waters both of which destabilized the water column.

The winter monsoon (November-February), in general, showed comparatively deep MLD (~30-40 m) all over the Bay except in the north and eastern Bay. The shallow MLD (~5-15 m) in the north and eastern Bay could be explained in the context of the presence of low salinity waters (<32 psu) during November-December and associated strong

stratification. As the winter progressed, the E-P showed a net evaporation and with no substantial input from rivers discharge the low salinity waters were confined to the northern part during January-February. As a result the area of deeper mixed layer expands further towards eastern boundary. The shallow MLD observed near the Sumatra coast in January was driven by the strengthened positive wind stress curl and the associated upward Ekman pumping. The deep MLD in the rest of the Bay was related to the weakest stratification that occurred in the Bay during winter monsoon compared to all other seasons. The wind speed, which showed a secondary peak in winter were able to initiate deeper wind-mixing as the stratification of the water column was the weakest and this gave rise to the deep mixed layer.

The seasonal variability of the barrier layer (BL) thickness showed strong coupling with wind stress curl, freshwater flux and prevailing circulation of the basin. The nutrient concentrations as well as chlorophyll *a* showed close correspondence with the changes in the mixed layer. During spring intermonsoon the upper ocean was oligotrophic and showed very low chlorophyll *a* concentrations ( $\sim 0.1 - 0.3 \text{ mg/m}^3$ ). This was because of the strongly stratified upper ocean due to the peak heating by incoming shortwave radiation. The mixed layer was very shallow as the weak winds during spring intermonsoon were unable to initiate strong wind-driven mixing. As a result there was no vertical transport of nutrients to the surface layer from subsurface making the upper ocean oligotrophic.

During summer monsoon the high nitrate as well as the chlorophyll *a* concentrations in the Indo-Sri Lanka region was driven by the upwelling. The upward Ekman pumping



associated with upwelling transports sub-surface nutrients from the nitracline to the surface layers and supports high biological productivity. In the northern Bay the higher concentration of nitrate was supplied by the river runoff. The observed enhanced chlorophyll *a* was supported by this nutrient input. Away from this region, the high stratification of the upper layers due to the freshwater input from precipitation as well as river runoff inhibited wind-driven mixing though the winds were strongest in summer monsoon. Accordingly, the nutrient input from sub-surface to the upper ocean also was curtailed. Thus, the shallow MLD and the oligotrophic upper ocean lead to the observed low chlorophyll concentrations ( $\sim 0.2 \text{ mg/m}^3$ ) in the rest of the Bay. In fall intermonsoon, the satellite-derived chlorophyll pigment concentrations showed pattern similar to that of summer monsoon with a reduced concentration indicating the tapering effect of summer monsoon. In winter, both the nitrate concentrations and the chlorophyll *a* concentrations were high along the western boundary. The EICC which moved southward during winter was capable of transporting some of the nutrients from the northern Bay towards the south along the western boundary and could explain the nutrient enhancement which in turn supported observed chlorophyll *a* concentrations.

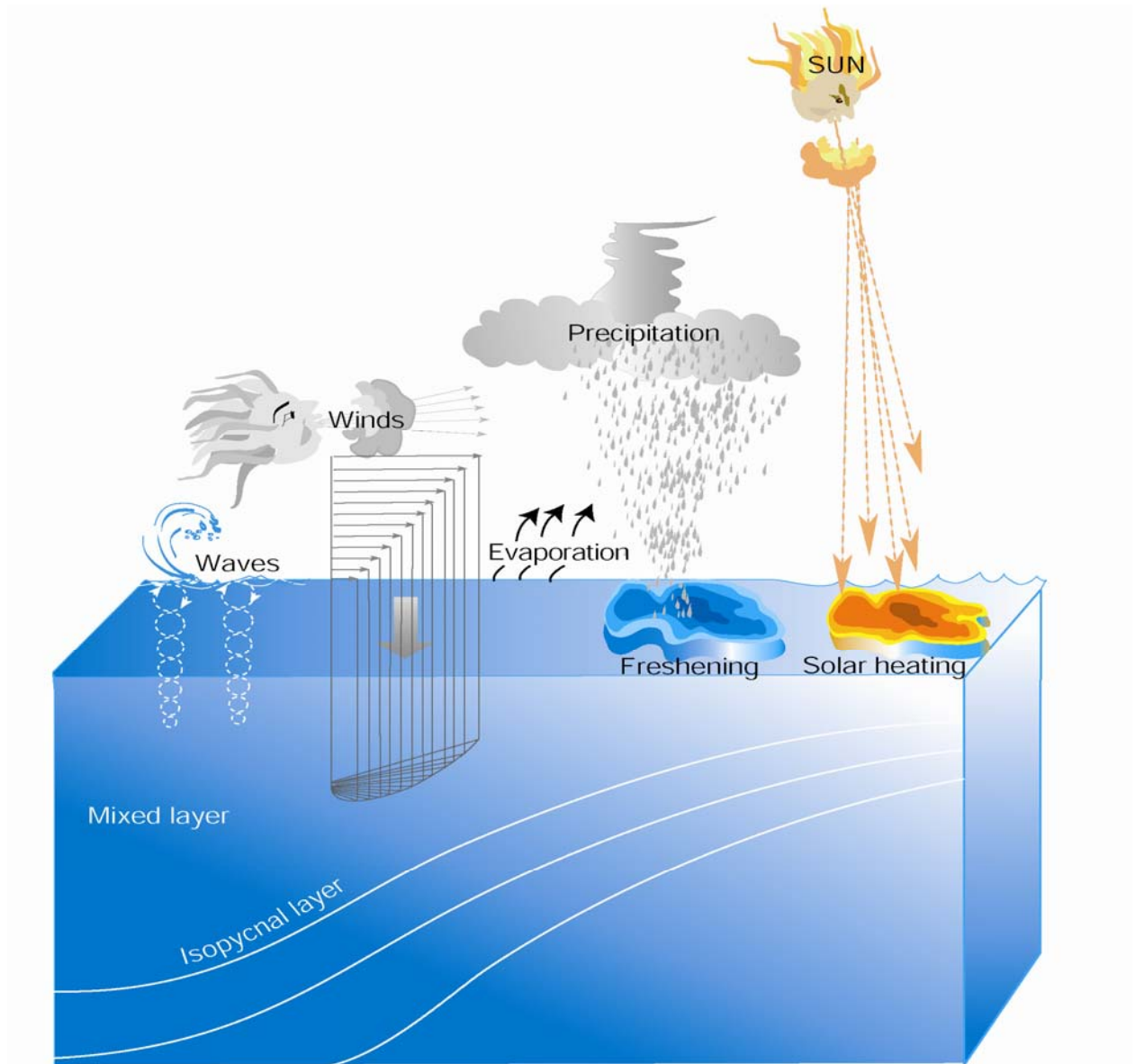
# Chapter 1 – Introduction

## 1.1 Oceanic Mixed Layer

The Ocean's effect on weather and climate is governed by processes that occur in the upper few tens of meters of the water column at the air-sea interface. The upper ocean is the most variable and dynamically active part of the marine environment that couples the underlying ocean to the atmosphere above through the transfer of mass, momentum and energy. It is through this layer that the atmosphere feels the ocean and hence the changes within this layer will regulate the ocean-atmosphere as a coupled system. Hence a correct representation of the processes occurring in ocean-atmosphere interface is absolutely essential for determining the large-scale upper ocean variability. In addition bulk of the biological productivity of the World Oceans, which is closely linked to climate through CO<sub>2</sub> regulation, critically depends on the physical and chemical changes taking place within this layer. Thus, on a global scale the upper ocean is one of the most important factors in determining climate of the earth system [*Kraus, 1977*]. The air-sea boundary processes and their relation to the upper ocean changes have been an ever-increasing subject of interest to the oceanographers and climate researchers.

Oceanic surface layer is a region of intense mixing and hence the properties within this layer are nearly homogeneous. This nearly homogeneous upper ocean layer is referred to as the mixed layer. The thickness of mixed layer is an important parameter in determining the quantity of heat that is available for exchange with atmosphere which is capable of triggering several ocean-atmosphere coupled processes such as convection, generation of tropical cyclones, etc. In order to model the ocean's climate variability

accurately information on the space-time variability of mixed layer is a prerequisite.



**Fig.1.1.1** Schematic representation of various factors that influence the upper ocean mixed layer (redrawn from *Prasanna Kumar and Narvekar, 2005*).

The mixed layer depth (MLD) also is an important parameter in determining the chlorophyll biomass and biological productivity of the upper ocean [*Morel and Andre, 1991; Longhurst, 1995*]. The MLD varies on several temporal scales ranging from diurnal, intra-seasonal, seasonal to inter-annual [*Weller and Farmer, 1992; Fischer, 1997*

& 2000] and the variability of MLD is directly linked to processes occurring in the mixed layer [Brainerd and Gregg, 1995].

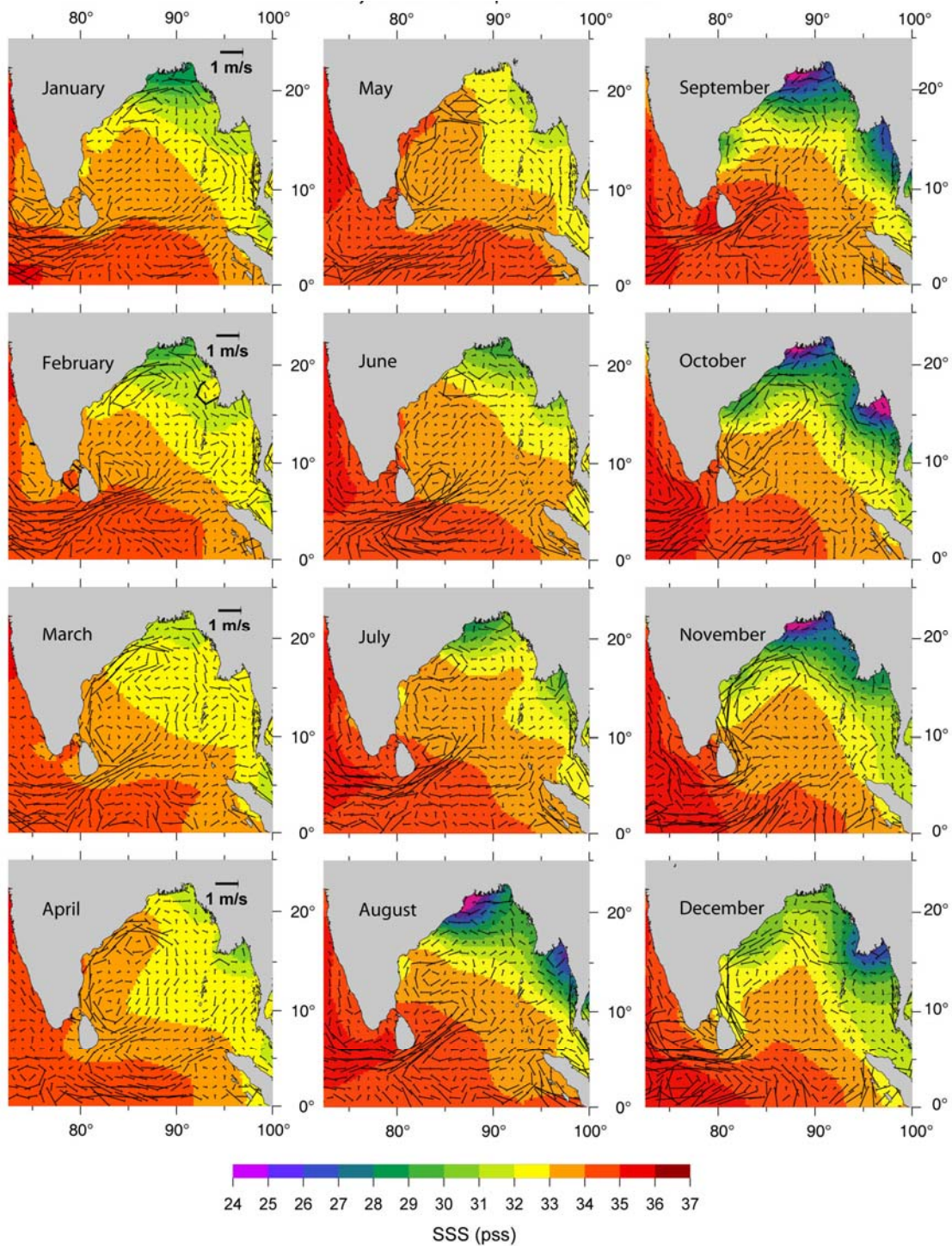
Atmospheric forcing that regulates mixing in the upper ocean are winds, waves, solar heating, evaporation and precipitation. Fig.1.1.1 gives a schematic picture of various factors affecting the mixed layer. The solar heating and precipitation stratify and stabilize the upper ocean, while the wind, wave action and evaporation destabilize it through mixing. Since the atmospheric forcing is highly variable on space-time scales, the geographical location, to a great extent, decides the structure and variability of the upper mixed layer.

## **1.2 Geographic Location and Oceanography of the Study Area**

The Bay of Bengal, situated in the eastern part of the northern Indian Ocean, is a tropical basin, which is landlocked in the north and is forced by semi-annually reversing wind system -- the monsoon. During winter (northeast) monsoon (November-February), the winds are weak (~5 m/s) and from northeasterly direction. These northeast trade winds bring cool and dry continental air mass to the Bay of Bengal. In contrast, during the summer (southwest) monsoon (June-September) the strong (~10 m/s) southwesterly winds bring humid maritime air into the Bay of Bengal. The unique feature of the Bay of Bengal is the large seasonal freshwater pulse, which makes the waters of the upper layers less saline and highly stratified. It also is a region of excess precipitation over evaporation [ $\sim 2 \text{ m yr}^{-1}$ , Prasad, 1997]. This fresh water input leads to the formation of strong halocline within the upper isothermal layer known as 'barrier layer' [Lukas and

*Linderstrom, 1991; Sprintall and Tomczak, 1992*]. Strong stratification associated with the barrier layer [*Vinayachandran et al., 2002*] curtails the vertical mixing leading to the formation of shallow mixed layers. Along with the fresh water the rivers also bring large sediment load ( $1387 \times 10^6$  tons of suspended solids annually) [*Subramanian, 1993*] in the northern Bay of Bengal making the surface waters turbid which curtails the light penetration. The fresh water input induces estuarine characteristics with reduced surface salinities over most of the Bay, which in turn hampers exchange processes between the atmosphere, surface and deep waters and consequently affects the biological and biogeochemical processes.

The semi-enclosed nature of the Bay of Bengal and its proximity to the equator together with immense quantity of fresh water [ $1.625 \times 10^{12} \text{ m}^3 \text{ yr}^{-1}$ , *Subramanian, 1993*] influx from Ganges, Brahmaputra and several peninsular Indian rivers contribute to the formation of a highly complex system of circulation in the Bay. The surface circulation within the basin, though reverses semi-annually, is not strictly in accordance with the wind reversal but appears to lead it. During the end of winter, in February, when the winds are still northeasterly, the current along the western boundary reverses and flows northward. This northward flowing East India Coastal current (EICC) peaks during March-April (spring intermonsoon), when the winds are weak but possess anticyclonic curl [*Shetye et al., 1993*]. Open-ocean circulation during this period is the best organized with an anticyclonic, subtropical gyre, and EICC forms the western limb of this circulation (Fig.1.2.1). In May, prior to the intensification of summer (southwest) monsoon, the spring-time anticyclonic circulation collapses and the EICC weakens. In July, when the southwest monsoon is at its full strength, the EICC weakens further and



**Fig.1.2.1** Monthly mean climatology of sea surface salinity from WOA05 [Antonov *et al.*, 2006] overlaid with geostrophic current vectors computed from sea-level anomaly (SLA). The merged SLA climatology was derived from Topex/Poseidon ERS1/2 satellites during the period 1992-2006.

even reverses to a southward flow in the northern part [*Shetye et al.*, 1991]. The open-ocean circulation at this time of the year consists of multiple gyres, re-circulations, meanders and eddies. In September, when the southwest monsoon weakens, the EICC reverses, flowing towards the south almost along the entire coast, forming a part of the cyclonic gyre. The southward EICC peaks in December and decays in January, completing its annual cycle.

The Bay of Bengal is traditionally considered to have low surface chlorophyll and low biological productivity compared to the Arabian Sea though both the basins are located in similar latitudinal belt and subjected to similar seasonally reversing atmospheric forcing. The reason for this is attributed to the strong near-surface stratification due to excess freshwater flux (low salinity) and relatively weaker winds during the summer monsoon, which makes the surface layers of the Bay of Bengal devoid of nutrients [*Prasanna Kumar et al.*, 2002]. Despite the low chlorophyll and primary productivity pattern in the Bay, sediment trap data shows that annual fluxes of organic carbon reach comparable rates in both the Arabian Sea and Bay of Bengal [*Ramaswamy and Nair*, 1994]. This is intriguing as there is no evidence of strong upwelling in the Bay of Bengal except for much localized ones close to the southwestern boundary during summer and traditional mechanisms of nutrient supply to the upper ocean waters cannot account for the observed annual flux of organic carbon from sediment trap. Recent studies indicated the presence of several cyclonic and anticyclonic eddies which alters the hydrography and biogeochemistry of the Bay of Bengal [*Prasanna Kumar et al.*, 2004; *Nuncio*, 2007]. These eddies (cyclonic) enhances the biological productivity by more than double (2 to 8 times) compared to the oligotrophic non-eddy region [*Prasanna Kumar et al.*, 2007].

Though the surface chlorophyll concentration remains low, the enhanced subsurface chlorophyll concentrations result in net increased biological production in the Bay. In addition to these eddies, the Bay of Bengal also is a site of severe tropical cyclones. The cyclones are generated during the spring (April-May) and fall (October) intermonsoons, and are associated with large-scale air-sea exchange, deepening of mixed layer and increased biological productivity through subsurface nutrient injection to euphotic zone.

### **1.3 Historical Background and Relevance of Present Work**

In the past, several studies attempted to understand the complex nature of the circulation and hydrography in the Bay of Bengal [Varkey *et al.*, 1996 and the references therein; Schott *et al.*, 2001; Shankar *et al.*, 2002]. An increasing number of recent studies suggested the role of remote forcing in aiding the semi-annual variability of the upper-layer circulation in the Bay of Bengal [Potemra *et al.*, 1991; Yu *et al.*, 1991; Perigaud and Delecluse, 1993; Prasanna Kumar and Unnikrishnan, 1995; McCreary *et al.*, 1993 & 1996, Shetye *et al.*, 1996; Vinayachandran *et al.*, 1996; Shankar *et al.*, 1996; Eigenheer and Quadfasel, 2000]. The remote forcing could arise due to a variety of mechanisms, such as planetary waves originating at the eastern boundary excited by the energy radiated by the coastal Kelvin wave, planetary waves generated by the variability in the local alongshore winds, and the interior Ekman pumping during the peak of summer and winter monsoons. It is natural to expect that these semiannual atmospheric forcing as well as the remote forcing would modulate the thickness of the upper ocean by altering the thermal and mechanical inertia of the layer.



Compared to the studies on circulation and hydrography, studies on the mixed layer in the Bay of Bengal are very few. A limited number of researchers studied the variability of the mixed layer depth for the global ocean [*Monterey and Levitus, 1997; Kara et al., 2003; de Boyer Montegut et al., 2004 & 2007a*] including the Bay of Bengal, while the rest of the studies were aimed at understanding the mixed layer variability of the Indian Ocean of which the Bay of Bengal formed a part. These studies can be categorized into three – studies based on (1) climatological data, (2) data from individual cruises, and (3) ocean models. *Rao et al. [1989]* studied the evolution of mixed layer depth in the tropical Indian Ocean (30°N-30°S, 30°E-120°E) based on monthly mean climatology on 2° latitude by 2° longitude grid from the Master Oceanographic Data Set (MOODS), which contains hydrographic data during the period 1948 to 1981. Subsequently *Rao and Sivakumar [2000]* using a subset of the World Ocean Atlas 1994 [*Levitus and Boyer, 1994*], which contains hydrographic data up to 1993, studied the annual and semi-annual variability of the thermal structure and heat budget of the mixed layer of the tropical Indian Ocean. *Shenoi et al. [2002]* using data from World Ocean Atlas 1994 [*Levitus and Boyer, 1994; Levitus et al., 1994;* ] compared various processes that are responsible for the mixed layer heat budget for both the Arabian Sea as well as the Bay of Bengal. Later using World Ocean Atlas 1998 [*Conkright et al., 1998*], which contains hydrographic data up to 1998, *Rao and Sivakumar [2003]* studied the seasonal cycle of salinity and its influence on the seasonal evolution of near-surface mixed layer depth in the northern Indian Ocean (0-30°N, 40°E-100°E). More recently, *Narvekar and Prasanna Kumar [2006]* studied the seasonal variability of the mixed layer in the central Bay of Bengal using a 2° latitude by 4° longitude climatology prepared from a comprehensive data base

extracted from National Oceanographic Data Centre (NODC, Washington) CD-ROM [Levitus *et al.*, 1994] which contained data during 1900-92, Responsible National Oceanographic Data Centre (RNODC, Goa) which contained data during 1976-2003 collected by Indian research ships, and ARGO data during the period 2001-2004. Thadathil *et al.* [2007] used World Ocean 2001 data along with data from Indian Oceanographic Data Centre (IODC) and Argo data up to September 2006 to generate monthly mean maps of MLD in the Bay of Bengal as a part of the study on the formation and seasonal variability of barrier layer.

Based on the individual *in situ* data collected during MONSOON-77 and MONEX-79 experiments Gopalakrishna *et al.* [1988] studied the influence of wind on the variability of the mixed layer in the northern Indian Ocean during different phases of summer monsoon. Murty *et al.* [1996] studied the time evolution of mixed layer at a stationary location in the northern Bay of Bengal (20°N, 89°E) during southwest monsoon of 1990 (18-31 August & 9-19 September) based on the data collected under Monsoon Trough Boundary Layer Experiment (MONTBLEX) programme. Subsequently, based on the data collected during summer monsoon (11-24 July) of 1991 in the northwestern Bay of Bengal Gopalakrishna *et al.* [2002] studied the impact of fresh water plume on the mixed layer depth and surface circulation. Swain *et al.* [2003] used a time series measurements of winds and waves at 13°N, 87°E during 15 July to 30 August 1999 as a part of the Bay of Bengal Monsoon Experiment (BOBMEX-99) to study the effect of wind and waves on the mixed layer depth due to forced mixing in the central Bay of Bengal. Using data collected from the Indian Exclusive Economic Zone (EEZ) under the Marine Research-Living Resources (MRLR) programme as well as data from National Institute of

Oceanography (NIO) hydro CD *Maheswari* [2004] studied the mixed layer and hydrographic characteristics off the west and east coast of India.

In addition to the above mentioned studies on mixed layer variability based on climatology and *in situ* data, there were also few modeling studies. Using 1.5 layer reduced gravity model *Behera* [1998] studied the response of mixed layer to Bay of Bengal cyclone. *Han et al.* [2001] studied the influence of precipitation minus evaporation (P-E) and river runoff in the Bay of Bengal on the dynamics, thermodynamics and mixed layer physics in the upper Indian Ocean. They showed that in the regions where precipitation exceeds evaporation ( $P-E > 0$ ) the model mixed layer was found to be thin because of decreased entrainment and increased barrier layer. Using a one-dimensional turbulent closure model *Prasad* [2004] studied the physical mechanism governing the seasonal evolution of mixed layer depth (MLD) along the two open ocean transect in the Arabian Sea and the Bay of Bengal and concluded that the surface forcing controls the MLD in the Bay of Bengal rather than the vertical salinity stratification. Using Ocean General Circulation Model (OGCM) as well as *in situ* hydrographic observations during BOBMEX-99 *Vinaychandran and Kurian* [2007] studied the structure and variability of mixed layer and barrier layer during summer monsoon. *de Boyer Montegut et al.* [2007b] studied the seasonal and inter-annual variability of mixed layer heat budget in the northern Indian Ocean using a OGCM and concluded that salinity stratification plays a clear role in maintaining a high winter SST in the Bay of Bengal and the presence of freshwater near the surface allows heat storage below the surface layer that can be recovered later by entrainment warming during winter cooling.

All of the above studies examined the role of wind-mixing, net heat flux and fresh water flux in explaining the mixed layer variability. None of the earlier studies addressed the role of advection, remote forcing and eddies in regulating the mixed layer on a basin-scale. The present thesis is an attempt to understand basin-wide variability of the mixed-layer in the Bay of Bengal on a seasonal scale not only by local forcing but also by remote forcing, advection and meso-scale eddies along with its coupling to nutrients and chlorophyll.

## Chapter 2 – Data and Methodology

In order to study the seasonal variability of mixed layer in the Bay of Bengal and its regulation of nutrients and chlorophyll in response to the atmospheric forcing, a suite of oceanographic, atmospheric and remote sensing data were used.

### 2.1 Hydrographic Data

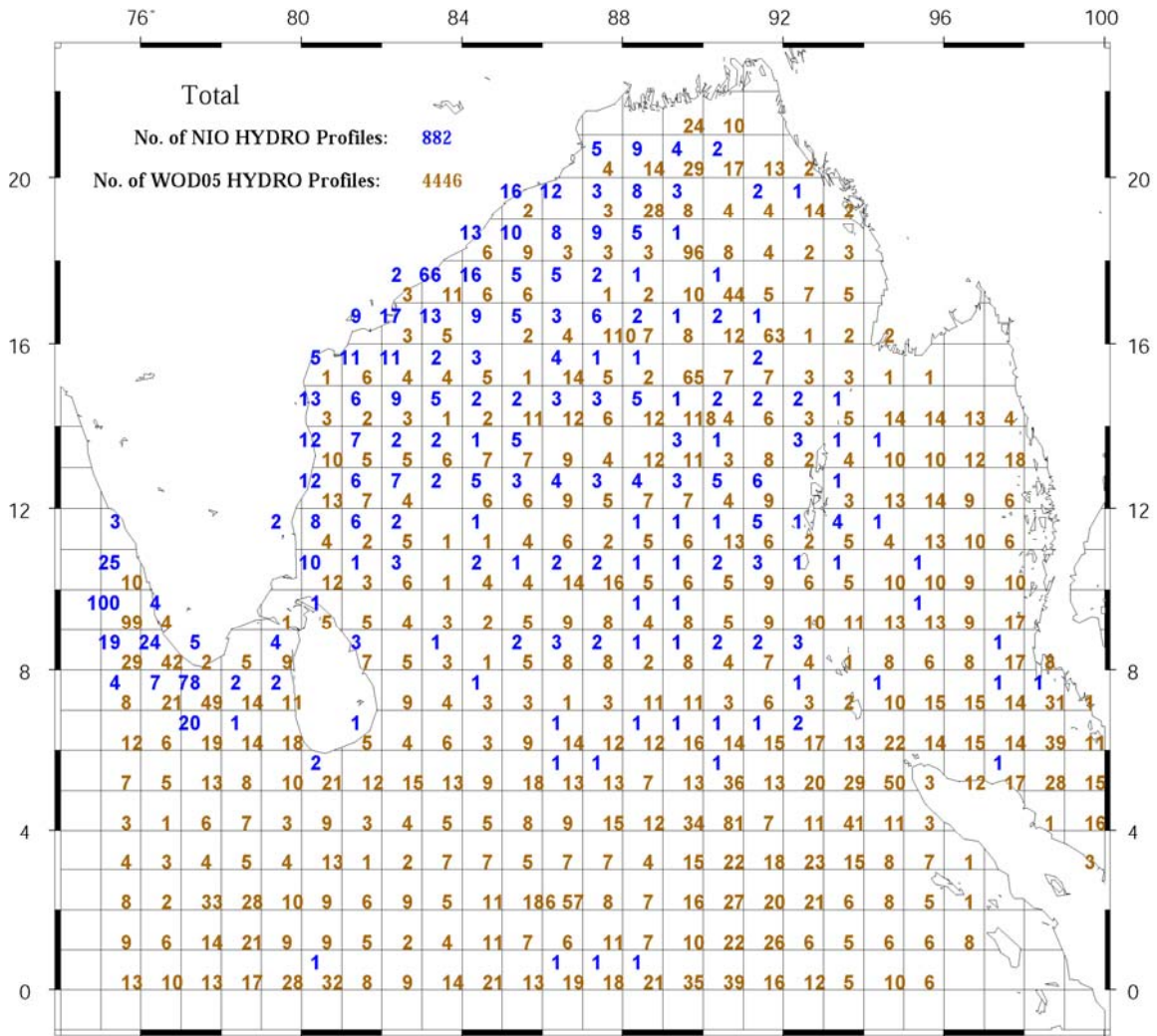
The major data set used in the study was the hydrographic data containing profiles of temperature, salinity, nitrate and chlorophyll *a*.

#### 2.1.1 Temperature and Salinity Data

The hydrographic data containing the profiles of temperature and salinity for the Bay of Bengal region (0-25°N, 75-100°E) were extracted from the following 3 sources:

1. The World Ocean Data base 2005 [Boyer *et al.*, 2006] which contained temperature and salinity data from Hydro-cast for the period 1919-2000 and conductivity temperature-depth (CTD) profiles for the period 1972–2003 ([http://www.nodc.noaa.gov/OC5/WOD05/pr\\_wod05.html](http://www.nodc.noaa.gov/OC5/WOD05/pr_wod05.html)).
2. Responsible National Oceanographic Data Center (RNODC) at National Institute of Oceanography (NIO), Goa which contained temperature and salinity data from Hydro-cast for the period 1972-1996 and CTD profiles for the period 1979-2006.
3. Argo data which contained the temperature and salinity profiles for the period 2002-2007 was extracted from <http://www.usgodae.org/argo/argo.html>.

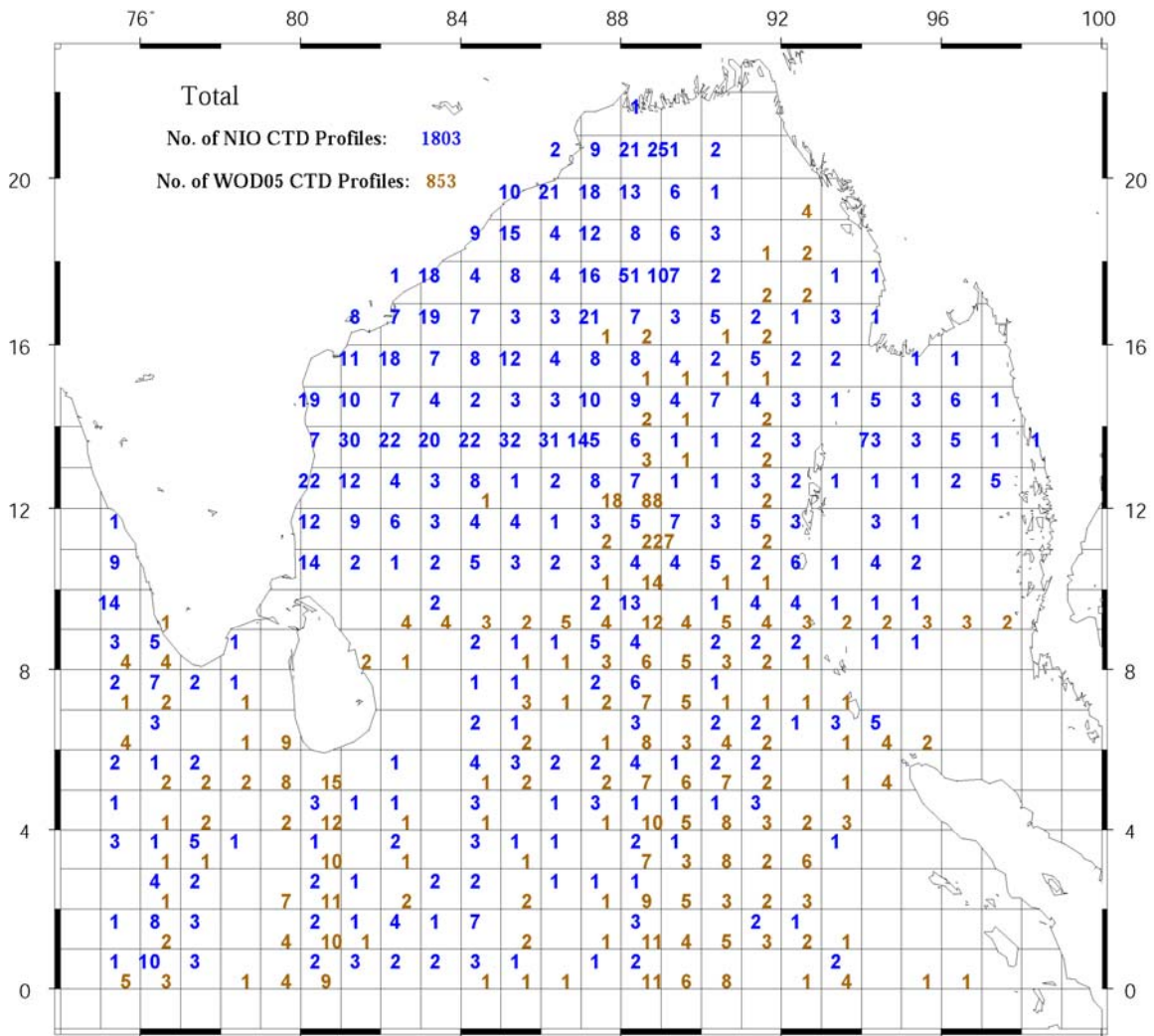
From the above 3 sources 7197 profiles of temperature and salinity from Hydro-cast, 2714 profiles from CTD and 4569 profiles from Argo were extracted. These profiles were subjected to the following quality control procedures to obtain quality data for further analysis.



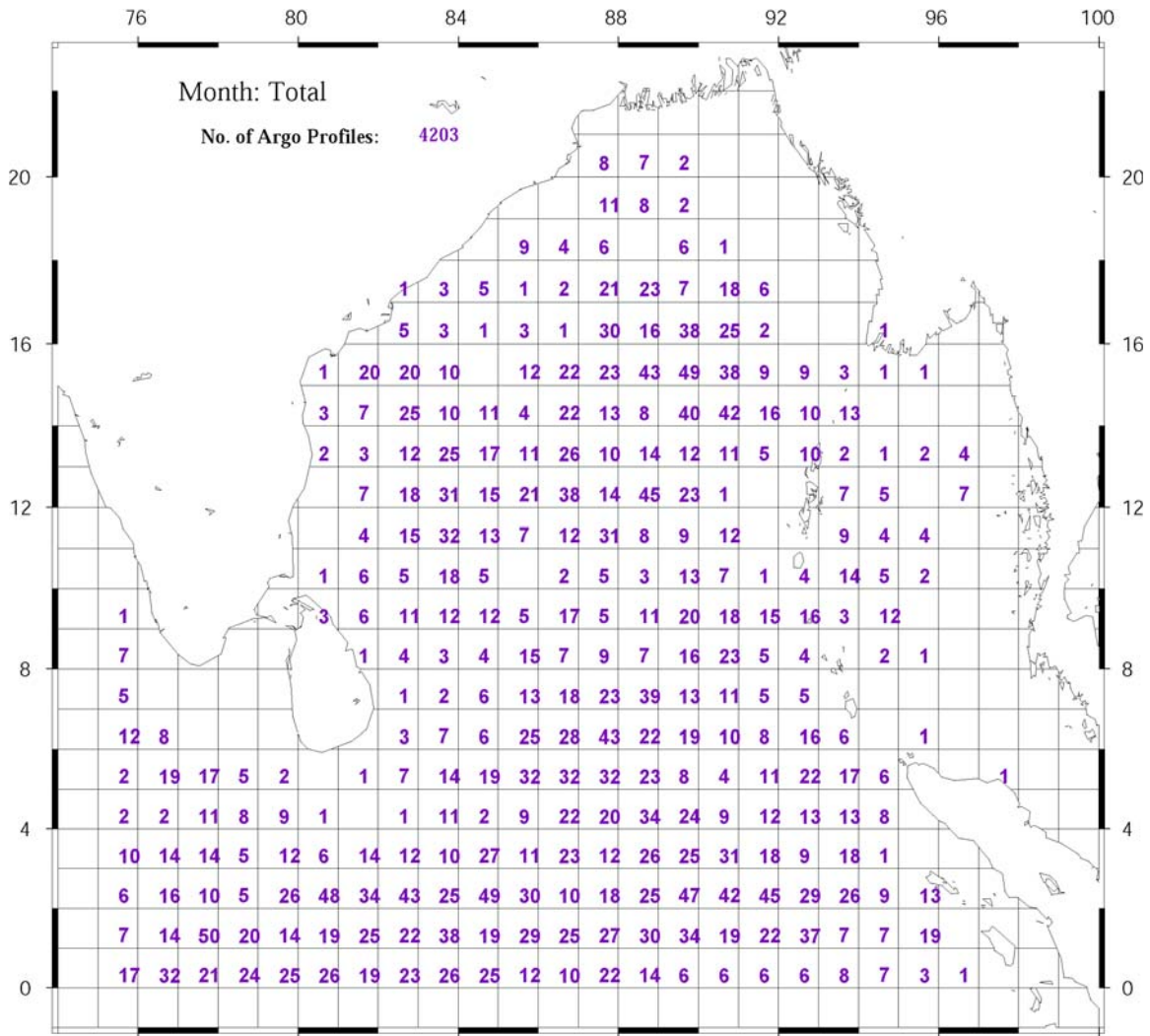
**Fig.2.1.1.1** Spatial distribution of number of Hydro-cast profiles from WOD05 and RNODC (NIO) after quality check in 1°latitude x 1°longitude in the Bay of Bengal.

At first the profiles with depth less than 50m were eliminated, as the objective of the study is to determine mixed layer depth, which may exceed 50m. The remaining data were physically examined and duplicate profiles as well as those with obvious errors

were excluded. After the quality control, the total number of Hydro-cast profiles were reduced to 5328, CTD profiles were reduced to 2656 and Argo profiles were reduced to 4203. From the quality checked data total number of profiles available under each category, such as Hydro, CTD and Argo were posted on a 1°latitude by 1° longitude grids and presented in Fig.2.1.1.1 to Fig.2.1.1.3.



**Fig.2.1.1.2** Spatial distribution of number of CTD profiles from WOD05 and RNODC (NIO) after quality check in 1°latitude x 1°longitude in the Bay of Bengal.



**Fig.2.1.1.3** Spatial distribution of number of Argo profiles after quality check in 1°latitude x 1°longitude in the Bay of Bengal.

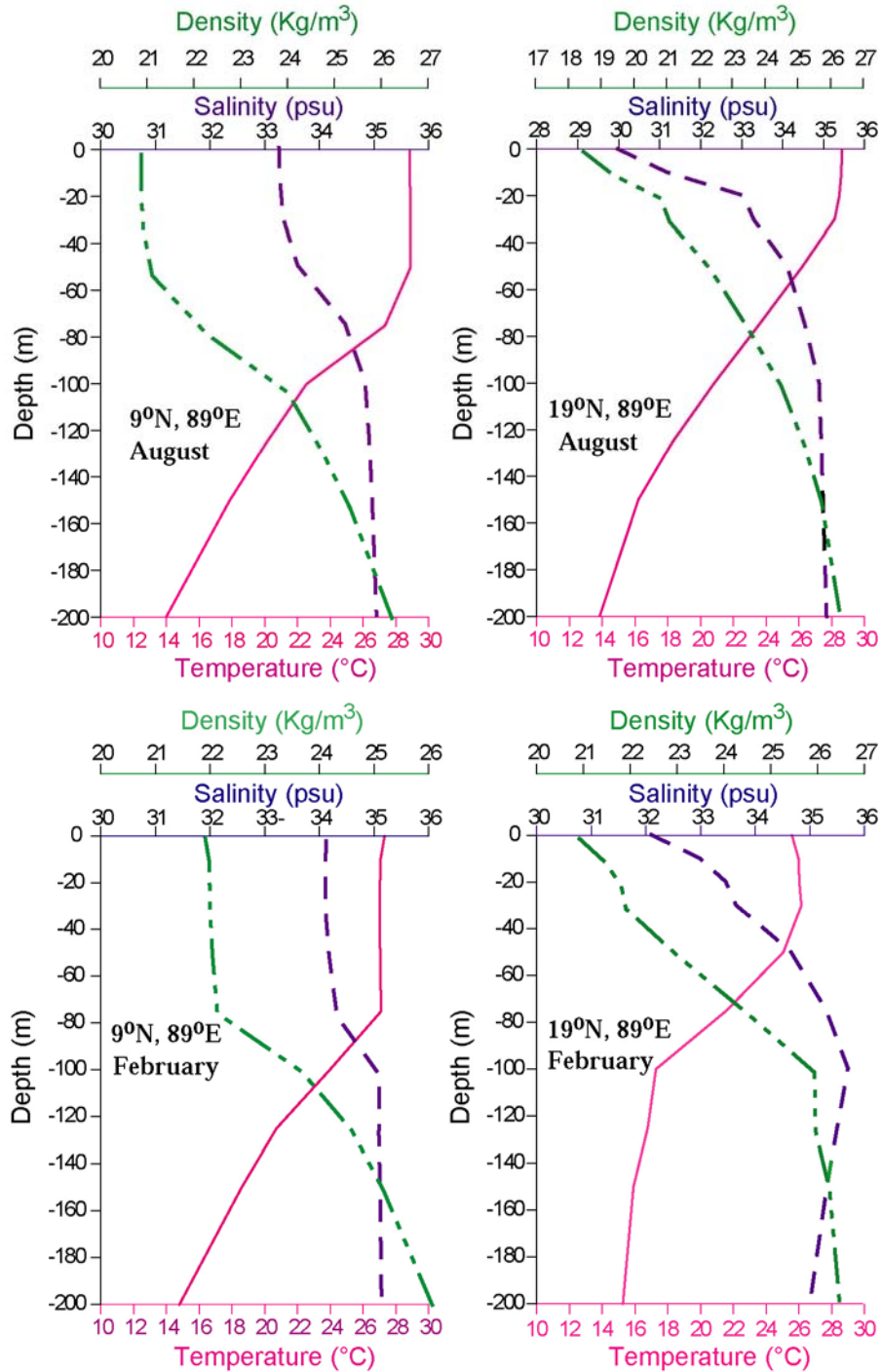
From the above temperature and salinity profiles density ( $\sigma_t$ ) was calculated [UNESCO, 1981] up to a depth of 500 m. The monthly mean climatology of temperature, salinity and  $\sigma_t$  were prepared on a 1° x 1° grid. These profiles were further used to determine sea surface temperature (SST) and sea surface salinity (SSS). The mixed layer depth (MLD), isothermal depth and barrier layer thickness were calculated from the monthly mean data as described in the following section.



### 2.1.2 Definition of Mixed Layer, Isothermal Layer and Barrier Layer

Two types of mixed layer depth (MLD) definitions have been most commonly used in the literature – (1) based on specifying a difference in temperature or density from the surface value [Wyrki, 1964; Levitus, 1982; Schneider and Muller, 1990] and, (2) based on specifying a gradient in temperature or density [Bathen, 1972; Lukas and Lindstrom, 1991]. It is important to examine the distribution of properties within the upper layer before any such criteria are applied. Since the Bay of Bengal comes under the semi-annual forcing of monsoons, the vertical profiles of temperature, salinity and sigma-t are presented for a 1-degree grid centered at 9°N and 19°N latitude along 89°E for the month of August and February (Fig.2.1.2.1), which represents the summer and winter conditions respectively.

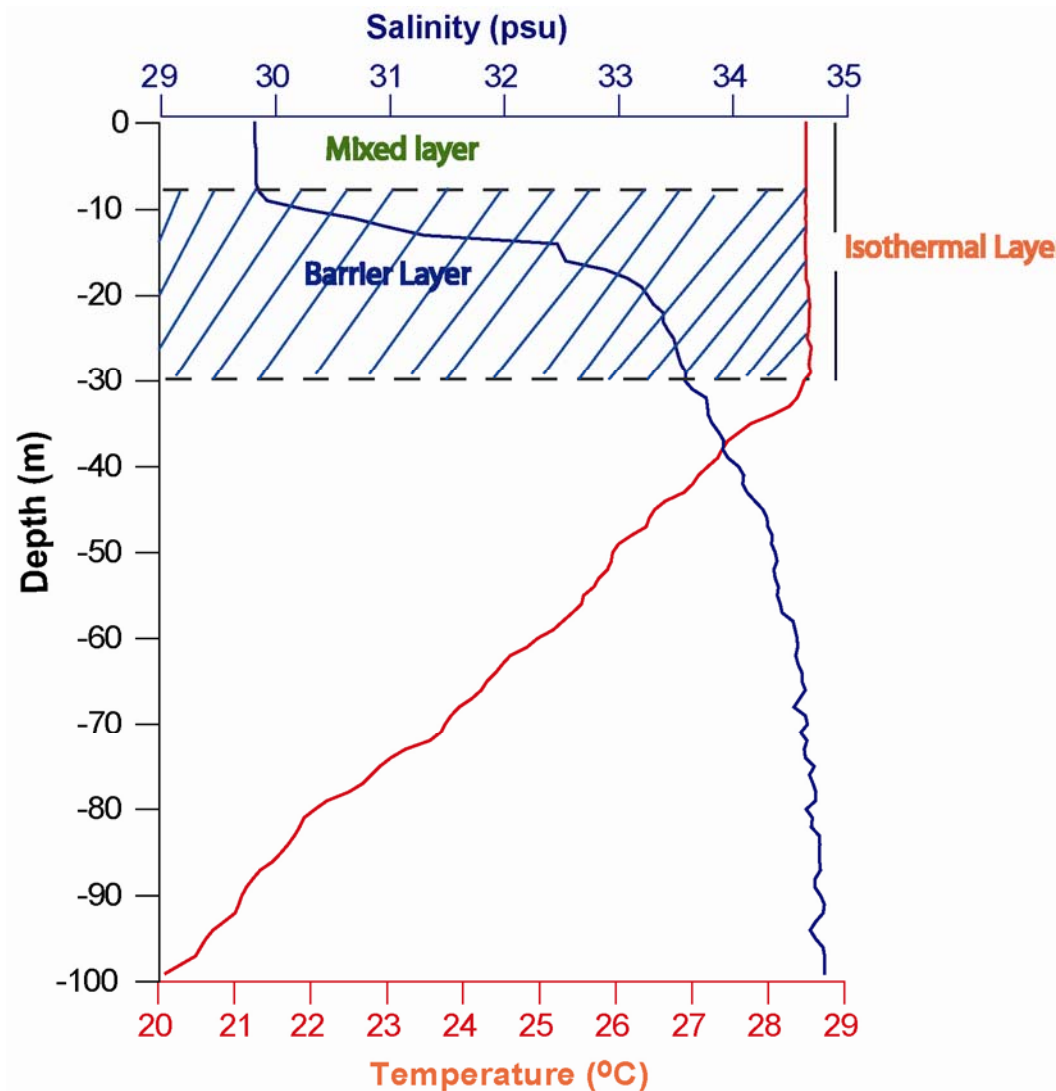
The vertical profiles indicated that the isothermal, isohaline and isopycnal layers, in general, coincided in the upper ocean irrespective of the season in the southern part of the Bay of Bengal (Fig.2.1.2.1 left panels), but in the northern Bay temperature and salinity showed a different vertical structure (Fig.2.1.2.1 right panels). In the northern Bay, the temperature showed an isothermal layer within which the salinity increased rapidly with depth. This is associated with freshening due to the river runoff as well as precipitation during summer. Hence, the criteria for defining the MLD should take into account the density variation rather than temperature or salinity. Since in the northern Bay density is controlled by salinity more than temperature, in the present study MLD is defined as the depth at which the density (sigma-t) exceeds  $0.2 \text{ kg m}^{-3}$  from its surface value. To numerically determine MLD, the monthly mean temperature, salinity and sigma-t profiles were interpolated onto 1 m-depth intervals by the cubic spline method.



**Fig.2.1.2.1** Vertical profiles of temperature (solid line, pink), salinity (broken line, purple) and density (sigma-t; dash-dot line, green) for August (top) and February (bottom) at 9°N (left) and 19°N (right) along 89°E.

Isothermal layer for the present study is defined as the depth at which the temperature decreased by 1°C from its surface value (Fig.2.1.2.2). The barrier layer is the layer within

the isothermal layer and below the mixed layer within which the salinity increased rapidly (blue stippled region in Fig.2.1.2.2). Barrier layer was numerically calculated by subtracting the MLD from the isothermal layer.

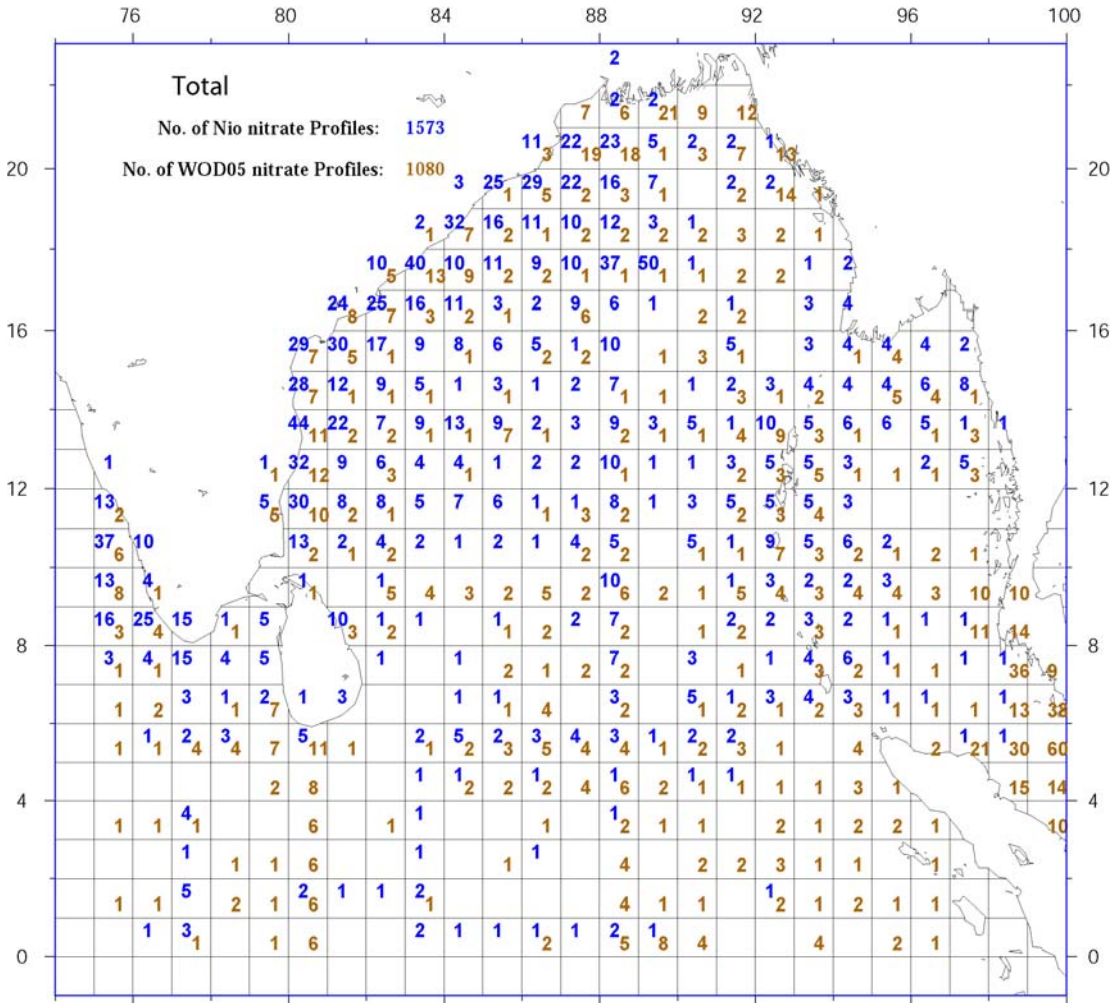


**Fig.2.1.2.2** Vertical profiles of temperature and salinity in the northern Bay of Bengal (19°N, 88°E) during August 2001 depicting the isothermal layer and barrier layer.

### 2.1.3 Nutrient Data

In this study only nitrate profiles from the nutrient database were used. The World Ocean Data base 2005 [Boyer *et al.*, 2006] contained the nitrate data for the period 1906-1999

while the RNODC (NIO) had the data for the period 1973-2006. The total number of nitrate profiles extracted from the above sources was 7406. From these the duplicate profiles were removed first and then the rest of the profiles were physically checked for any obvious ambiguity, which was removed subsequently. The quality control procedure



**Fig.2.1.3.1** Spatial distribution of number of nitrate profiles from WOD05 and RNODC (NIO) after quality check in 1°latitude x 1°longitude in the Bay of Bengal.

reduced the total number of profiles to 2653. The number of profiles available at each of the 1° latitude x 1° longitude grid is shown in Fig.2.1.3.1 Since the total number of profiles in each of the one-degree grid itself were less, these data were grouped together

in time to produce seasonal mean. The seasons considered for this purpose is defined as

*Spring intermonsoon*    *March-May*

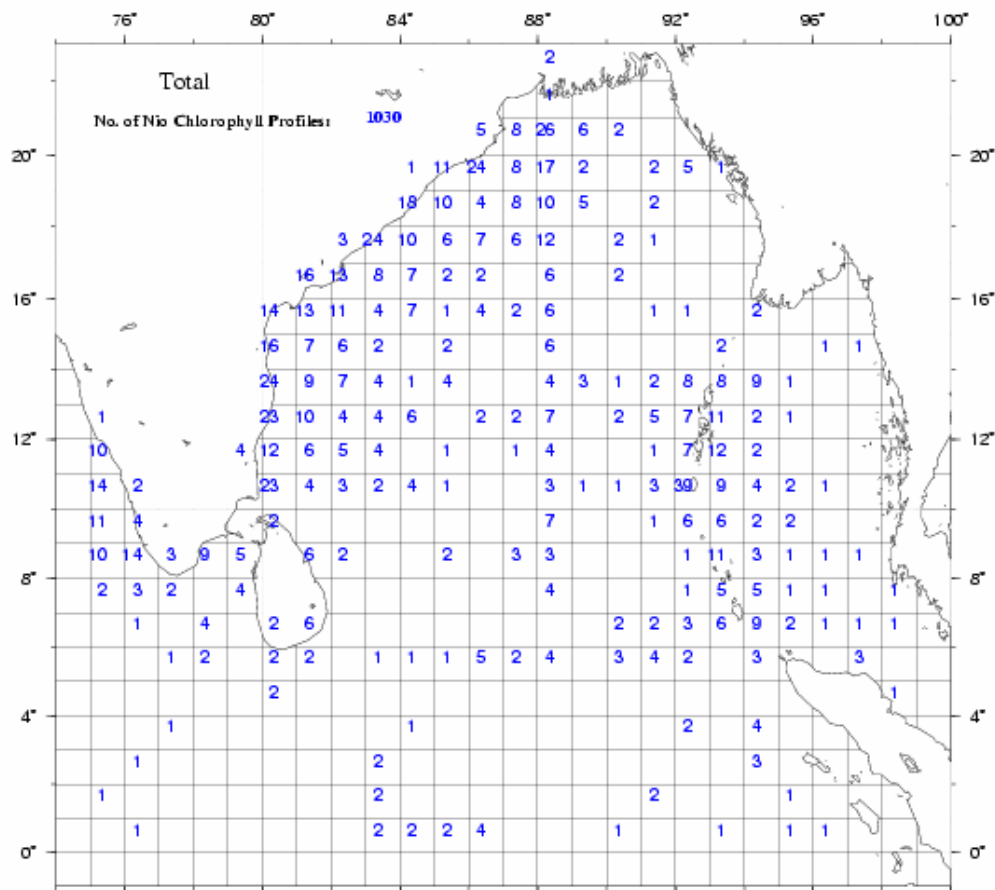
*Summer monsoon*        *June-August*

*Fall intermonsoon*      *September-October*

*Winter monsoon*         *November-February*

Since spatial coverage of data during fall intermonsoon was very poor and was confined to western Bay of Bengal, this season was not considered.

### 2.1.4 Chlorophyll Data

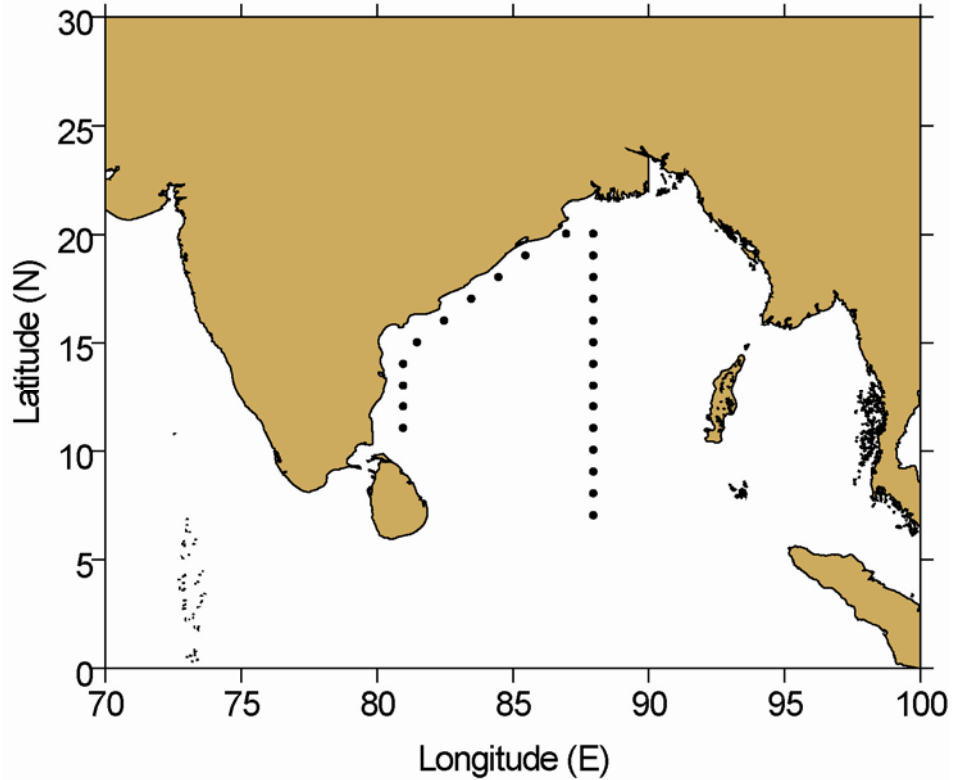


**Fig.2.1.4.1** Total number of Chlorophyll *a* data after quality check in the Bay of Bengal during 1951- 2006

The chlorophyll *a* profiles were taken from RNODC (NIO), which contained data for the period 1951-2006. The total number of chlorophyll *a* profiles were 1060 and after the quality control procedure, similar to that of nitrate, the number of profiles reduced to 1030. The number of chlorophyll *a* profiles available in each of the 1° latitude x 1° longitude grid was shown in Fig.2.1.4.1. Since the total number of profiles in each of the one-degree grid itself was less, these data were grouped together in time to produce seasonal mean. During fall intermonsoon spatial coverage of data was very poor and was confined to western Bay of Bengal, hence this season was not considered.

### **2.1.5 Hydrographic data for studying effect of meso-scale variability on mixed layer depth**

Apart from the above mentioned hydrographic data, a set of high resolution *in situ* data collected during Bay of Bengal Process Studies (BOBPS) has been utilized to delineate the effect of meso-scale variability on mixed layer depth. The data includes the vertical profiles of temperature and salinity collected using SeaBird CTD during four seasons along 88°E and along the western boundary of the Bay of Bengal (Fig.2.1.5.1). The measurements were carried out during summer (6 July to 2 August, 2001), fall intermonsoon (14 September to 12 October, 2002), spring intermonsoon (12 April to 7 May, 2003), and winter (25 November 2005 to 4 January 2006). CTD salinities were calibrated against water samples collected simultaneously by a rosette sampler and analysed with ship-board Guildline 8400 Autosol.



**Fig.2.1.5.1** Map showing station location (dark filled circles) along the central (88°E) and western Bay of Bengal where temperature and salinity profiles were collected.

From the temperature and salinity profiles, static stability parameter was computed following *Pond and Pickard* [1983]

$$E = -\frac{1}{\rho} \frac{\partial \rho}{\partial z}$$

Where E is the static stability parameter ( $\text{m}^{-1}$ ),  $\rho$  is the density ( $\text{kg m}^{-3}$ ) of the water and z is the depth (m).

### 2.1.6 River Runoff Data

The monthly mean climatology of river discharge of 6 major rivers Ganges, Brahmaputra, Irrawady, Godavari, Krishna and Cauvery were taken from Global Runoff data Centre, Germany (<http://grdc.bafg.de/servlet/is/2781>).

## 2.2 Atmospheric Data

Meteorological data were extracted from the National Oceanographic Centre (NOC), Southampton, climatology (formerly Southampton Oceanographic Centre, SOC) (<http://www.noc.soton.ac.uk/ooc/CLIMATOLOGY/noc11.php>) in the domain (0-25°N and 75-100°E) for the period 1980-1993, which contained the monthly mean climatology of meteorological parameters such as incoming short wave radiation, wind speed, evaporation, precipitation and net heat flux on 1° longitude by 1° latitude grid.

## 2.3 Remote Sensing Data

Since the *in situ* chlorophyll data was limited in both space and time, chlorophyll pigment concentrations derived from global 9-km monthly mean imagery of Sea-viewing Wide Field-of-view Sensor (SeaWiFS) for the period September 1997 to December 2007 (<http://reason.gsfc.nasa.gov/OPS/Giovanni/ocean.seawifs.shtml>) were used in addition to *in situ* chlorophyll *a* profiles to compare with surface distributions. From these data the climatological seasonal means were calculated for spring intermonsoon, summer monsoon, fall inter monsoon and winter monsoon. Merged sea-level anomalies of Topex/Poseidon ERS1/2 series satellites obtained from AVISO live access server (<http://las.aviso.oceanobs.com>) was also used for the period October 1992 to January 2006, which gives 7-day snapshots having a spatial resolution of 1/3<sup>rd</sup> of a degree, to prepare monthly mean climatology of sea-level anomaly. From the sea-level height anomalies velocities were computed assuming the geostrophic relation [Pond and Pickard, 1983]



$$2\Omega \sin(\phi).V = g \tan(i)$$

where  $\Omega$  is the earth's angular velocity,  $\phi$  is the latitude,  $V$  is the velocity and  $\tan(i)$  is the slope of the sea surface.