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:


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.

![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.](image)

**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 [Wyrtki, 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 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.

![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.](image)

**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 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

![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.](image-url)
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 $1^\circ$ latitude x $1^\circ$ 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 Autosal.
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 (m$^{-1}$), $\rho$ is the density (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/CLIMATOLOGY/noc11.php](http://www.noc.soton.ac.uk/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](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](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 1/3rd 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]
$2\Omega \sin(\phi) \cdot V = g \tan(i)$

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.