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 CO₂ 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.
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 (~ 2 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 brings large sediment load (1387 x 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 intern 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 x 10^{12} m^3 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 (cycloic) 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 *Maheswaram* [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 Montégut 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.