

## Chapter 7 – Summary and conclusions

The variability of the upper ocean including the mixed layer and the barrier layer has been studied in the context of atmospheric forcing and remote forcing, and its role in regulating the nutrients and chlorophyll in the Bay of Bengal on a seasonal scale. For this a suite of *in situ* as well as remote sensing data were used. The *in situ* data consisted of temperature and salinity profiles derived from (1) World Ocean Data Base [Boyer *et al.*, 2006] consisting of Hydro-cast during the period 1919-2003 and CTD for the period 1972-2003, (2) Responsible National Oceanographic Data Centre (RNODC) at National Institute of Oceanography which has data from Hydro-cast during 1972-1996 and CTD during 1979-2006 collected from Indian research ships and (3) Argo data during 2002-2007. 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. The nitrate data were extracted from the World Ocean Data Base during 1906-1999 and RNODC for the period 1973-2006, while chlorophyll data were taken from the RNODC during the period 1951-2006. In all there were 7406 nitrate profiles and 1060 chlorophyll *a* profiles. All the above hydrographic data were quality controlled to first eliminate duplicate profiles and then each profile were visually checked for obvious errors and removed. Finally profiles with depth less than 50 m were removed as the mixed layer in the Bay of Bengal is expected to exceed more than 50 m. This quality control procedure reduced the total number of Temperature-Salinity profiles from Hydro-cast to 5328, CTD to 2656 and Argo to 4203. The quality control reduced the nitrate profiles to 2653 and chlorophyll *a* profiles to 1030. The temperature and salinity profiles were used to calculate the density

(sigma-t). From these profiles the monthly mean climatology of temperature, salinity and sigma-t were prepared on a  $1^{\circ} \times 1^{\circ}$  grid.

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.

Since adequate nitrate and chlorophyll *a* profiles were not available to create a monthly mean climatology, they were prepared as a seasonal climatology on a  $1^{\circ} \times 1^{\circ}$  grid. The seasons considered for this purpose were spring intermonsoon (March-May), summer monsoon (June-August), fall inter-monsoon (September-October), and winter monsoon (November-February). However, as the nitrate as well as chlorophyll *a* data were extremely limited during the fall intermonsoon, this season was not considered for the analysis.

The monthly mean climatology of discharge of 6 major rivers Ganges, Brahmaputra, Irrawady, Godavari, Krishna and Cauvery were taken from Global Runoff data Centre, Germany to examine the river discharge in the context of low surface salinity distribution in the Bay of Bengal.

In addition to the monthly mean climatology, the high resolution *in situ* data collected during Bay of Bengal Process Studies (BOBPS) has also been utilized to delineate the effect of meso-scale variability on mixed layer depth. The temperature and salinity profiles were obtained using CTD at 1-degree from 7°N to 20°N along the central (88°E) and from 11°N to 20°N along the western boundary of the Bay of Bengal. 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).

The atmospheric data used were monthly mean climatology of the incoming short wave radiation, wind speed, evaporation, precipitation and net heat flux on 1° longitude by 1° latitude grid obtained from National Oceanographic Centre (NOC), Southampton for the period 1980-1993. The remote sensing data used for the study were 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 amplitude of the seasonal cycle of incoming short wave radiation (SWR) was about 120 W/m<sup>2</sup> with lowest during November – December (~165 W/m<sup>2</sup>) and highest during March-April (~285 W/m<sup>2</sup>). The seasonal cycle showed two warming and cooling periods. The highest SWR was during March-April followed by September, while the lowest was during November-February followed by June-August. The highest spatial variability

occurred in May when SWR varied  $80 \text{ W/m}^2$  from south to north within the basin. The least spatial variability occurred in January and October which was about  $20 \text{ W/m}^2$ .

The amplitude of the seasonal cycle of net heat flux (NHF) was  $220 \text{ W/m}^2$  with highest net heat gain by the ocean during April ( $\sim 160 \text{ W/m}^2$ ) and the highest net heat loss by the ocean in December ( $\sim 60 \text{ W/m}^2$ ). The NHF showed a seasonal cycle with two periods of high heat gain by the ocean, the highest during March-April followed by October. The ocean lost heat of about  $20 \text{ W/m}^2$  during November-December from the northern Bay while the gain was the least in June. The highest spatial variability was in December ( $\sim 140 \text{ W/m}^2$ ) and the least was in September ( $\sim 50 \text{ W/m}^2$ ).

Consistent with the seasonality of the SWR and NHF, the sea surface temperature (SST) showed a strong seasonal cycle with two periods of warm and two periods of cool SST. The warming occurred during spring (April-May) and fall (October) intermonsoons, while cooling was in winter (January-February) and summer (August). There was a time lag of about a month between the atmospheric forcing by way of SWR and NHF and corresponding ocean's response in terms of SST. The amplitude of the seasonal cycle was about  $6^\circ\text{C}$  with coldest SST of about  $25^\circ\text{C}$  in the north during January and warmest SST of about  $31^\circ\text{C}$  in the central part of the eastern boundary during May. The highest spatial variability occurred during January when SST varied  $4^\circ\text{C}$  from south to north. The spatial variability was the least in October, which was about  $1.5^\circ\text{C}$ . Note that the highest and least spatial variability in SST was also closely coupled to that of atmospheric forcing. A characteristic feature in the time evolution of the spatial distribution of SST was the appearance of a thermal front with a region of cold water around Sri Lanka in

May. The thermal front developed further in June-July with expansion of cold water region towards the peninsular India. The thermal front was the strongest in August with coldest SST of 26.5°C and with a gradient of about 3°C from southern tip of peninsular India to south of Sri Lanka. The thermal front dissipated by September. This feature was not associated with atmospheric forcing due to SWR or NHF, but with the wind.

The amplitude of the seasonal cycle of wind speed within the basin was 6 m/s with lowest wind speed of about 4 m/s in March and October, and highest wind speed of 10 m/s in June. The highest spatial variability occurred during June when wind speed varied by 6 m/s from south to north. The least spatial variability occurred during March, which was 1 m/s. The seasonal cycle of wind speed in the northern Bay (north of 15°N) showed semiannual cycle with high wind speed during summer followed by winter, while low wind speed was during spring and fall intermonsoons. The wind stress curl showed highest positive value of  $20 \times 10^{-8}$  Pascal/m along the eastern part of Sri Lanka during June to August. This positive wind stress curl was capable of driving an upward Ekman pumping which in turn could transport cold sub-surface waters to the surface layer. Thus, the observed cold waters and the thermal front around Sri Lanka and the southern part of the peninsular India during June to August were linked to the process of upwelling in the Indo-Sri Lanka region.

The sea surface salinity (SSS) showed very strong seasonality, especially in the northern Bay. The amplitude of the annual cycle was about 8.5 psu with lowest salinity of 26.5 psu in the north during October and highest SSS of about 35 psu in the southern Bay during June-November. The highest spatial variability occurred during October when SSS varied

by 8.5 psu from north to south while the least spatial variability occurred in May, which was about 2 psu. The observed annual cycle of SSS could be understood in the light of the fresh water flux (E-P) and the freshwater discharge from rivers emptying into the Bay of Bengal.

The freshwater flux showed an annual cycle with the basin receiving excess precipitation over evaporation. The basin received highest excess precipitation of 440 mm/month in July and the highest evaporation of 120 mm/month was in December. The highest spatial variability occurred during July when E-P varied from 40 mm/month to -440 mm/month. The least spatial variability occurred during May, when E-P varied from 80 mm/month to -60 mm/month. The annual variability of E-P in the northern Bay (north of 15°N) showed a net evaporation from December-April and net precipitation from June-September. The monthly mean climatology of river discharge of 5 major rivers Ganges, Brahmaputra, Irrawady, Godavari, and Krishna showed the dominance of freshwater discharge during July to October. Thus, the observed rapid decrease of SSS in the northern Bay during June to October was tightly coupled to the freshening of the surface waters by the negative fresh water flux as well as the river water discharge into the northern Bay. The seasonal circulation redistributed the fresher water influencing the ambient salinity. In the southern Bay salinity remained almost same except during June to October when the high salinity waters (35 psu) of the Arabian Sea origin is advected into the Bay of Bengal. Since the freshwater input was from the peninsular rivers, which are located in the northern part of the Bay along the eastern and western boundaries, it is important to decipher the variability of the northern and southern Bay separately. In the northern Bay, north of 15°N, the amplitude of the annual cycle of SSS was about 6.5 psu

with the highest salinity in May (~33 psu) and lowest (~26.5 psu) in October. In the southern Bay the amplitude of the annual signal was about 0.5 psu and this was associated with the intrusion of the high salinity waters from the Arabian Sea.

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 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. In May, however, the shallow MLD was confined to the region north of 16°N. Another region of comparatively shallow MLD (~25 m) was seen in a band between 6° and 9°N. The rest of the basin, however, showed deep MLD (30-35 m). The observed MLD variability could be understood in the light of the prevailing ocean-atmospheric conditions. The incoming solar radiation peaked during March-April with a value of 280-290 W/m<sup>2</sup> and the net heat flux also was the highest 150-160 W/m<sup>2</sup>. The basin-wide winds were the weakest during this period (~4 – 5 m/s), except near the western boundary in April where a core of high wind speed was noticed and a strong negative wind stress curl. The shallow MLD in March-April was driven by the strong stratification induced by peak solar heating and subsequent highest net heat gain by the ocean. 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 led to 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 downwelling and deepens the mixed layer. The co-location of comparatively deep MLD (>25 m) and strong negative wind stress curl ( $\sim -20 \times 10^{-8}$  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 downwelling and augments the deepening of the mixed layer.

The shallow MLD in the northeastern Bay in May was due to the presence of low salinity waters (~ 32.5 psu) along with the high incoming solar radiation (270-280 W/m<sup>2</sup>) which increased the stratification. The moderate winds (5 – 5.5 m/s) in the northeastern region were unable to drive strong wind-mixing and hence the MLD was shallow. Comparatively shallow MLD in a band between 6° and 10°N east of Sri Lanka and southern tip of India was due to the upward Ekman pumping associated with the positive wind stress curl in this region. 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.



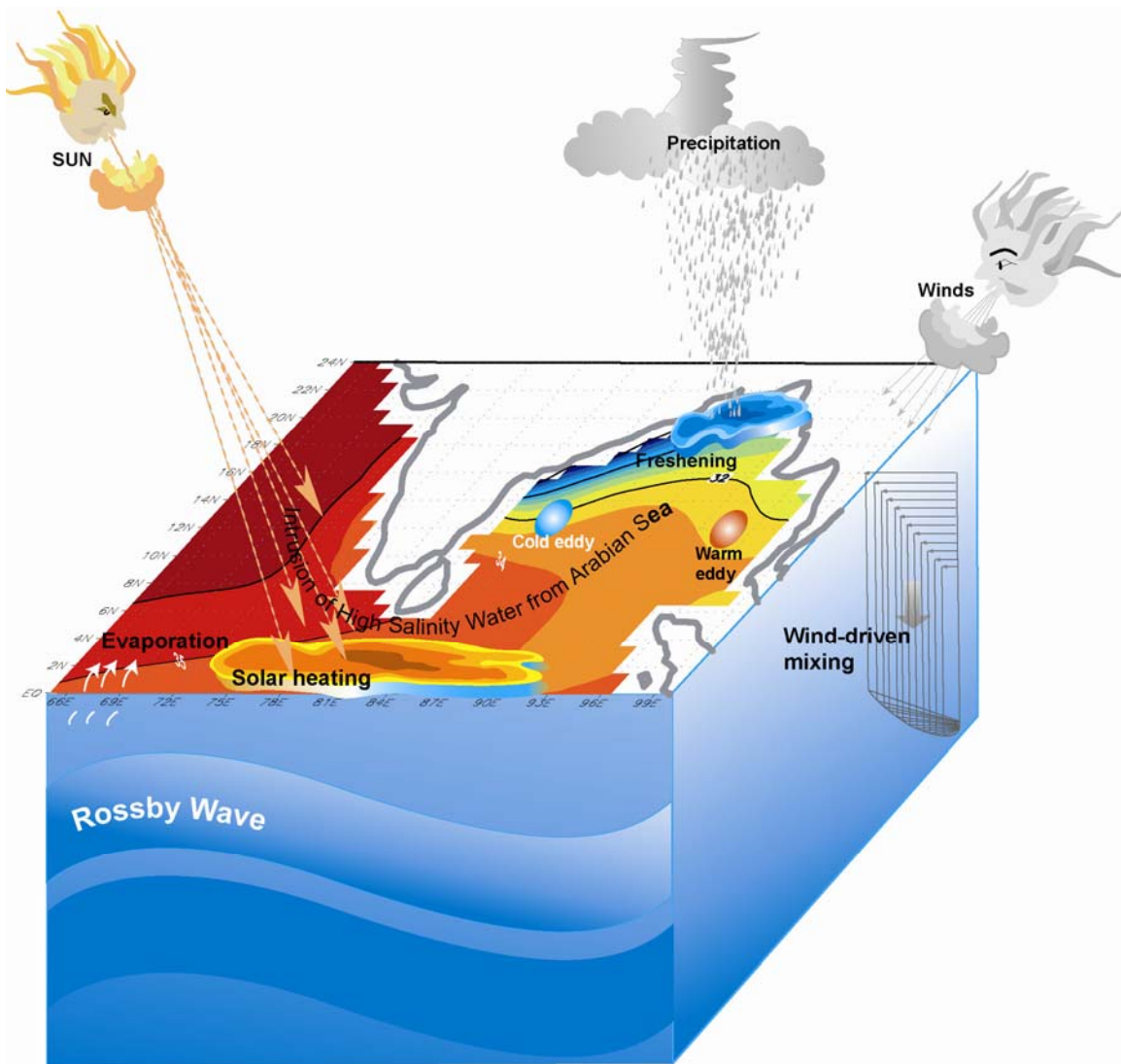
During summer monsoon a band of deep MLD between equator and 6°N joined the deep MLD region seen closer to the western boundary towards the end of spring intermonsoon. However, the northern and eastern part of the Bay had shallow MLD. With the progress of summer monsoon, the region of deep MLD expanded towards the central and northern Bay. The region around Sri Lanka showed a progressively shallow mixed layer with time during summer monsoon which also showed eastward expansion with time. The observed pattern of MLD variation could be explained in the following manner. Though the wind speed was the highest during summer monsoon 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. An examination of the monthly mean climatology of river discharge of 5 major rivers Ganges, Brahmaputra, Irrawady, Godavari, and Krishna showed that the freshwater discharge dominated during July to October. 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. Note that the upper ocean was very warm with SST in excess of 28.5°C, which 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. This process of upwelling was also evident from the cold SST and the observed thermal front seen around Sri Lanka and southern part of the peninsular India. 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. An examination of SSS showed that the high salinity waters from the Arabian Sea were progressively advected into the central Bay around Sri Lanka during summer monsoon. 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 sets in, the shallow MLD which was confined to northern Bay, north of  $18^{\circ}\text{N}$ , was seen extending southward to  $15^{\circ}\text{N}$  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  $29^{\circ}\text{C}$  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. As seen from the data, the river discharge was dominant during July to October and hence the low salinity of the surface water was the manifestation of this influence. 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 comparatively high wind speed and the presence of high salinity waters both of which destabilized the water column.

The winter monsoon, 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 river 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.



**Fig.7.1** Schematic representation of local and remote forcing that influence the depth of the mixed layer. Colour shading is the climatological monthly mean salinity for August from WOA05 [Antonov *et al.*, 2006] showing the intrusion of high salinity waters from the Arabian Sea. The local forcing that affect the MLD are the precipitation and river runoff, solar heating, wind-mixing and meso-scale eddies (cold-core eddy in blue and warm-core eddy in red). The remote forcings are the intrusion of high salinity waters from the Arabian Sea and propagation of Rossby waves.

Thus, the mixed layer depth in the Bay of Bengal was controlled by a combination of local forcing as well as remote forcing. Local forcing were freshening of the surface waters due to excess precipitation over evaporation (fresh water flux) and river runoff,

surface heating due to incoming short wave radiation (heat flux) and wind-driven mixing (momentum flux). In addition to this, the meso-scale eddies which are ubiquitous in the Bay of Bengal also influenced the MLD. The remote forcing included advection of high salinity waters from the Arabian Sea and propagating Rossby waves. These local and remote forcing that influenced the MLD in the Bay of Bengal is depicted in Fig.7.1.

The seasonal variability of the barrier layer (BL) thickness showed strong coupling with wind stress curl, freshwater flux and prevailing circulation of the basin. On a basin-scale the thickness of the BL was the least in spring intermonsoon compared to the rest of the season and also the spatial variability was the least. This was primarily because the fresh water input into the Bay during spring intermonsoon either by river run-off or by precipitation was the least. The prevailing weak winds and very strong thermal stratification due to peak heating reduced the BL thickness to minimum. However, the negative wind stress curl near the northwestern Bay during March lead to an increase in the BL. Along the equator the spring-time Wyrтки jet flowing from west to east as well as the negative wind stress curl drove down-welling and sinking which increased the BL close to equator.

During summer the thick BL along the equator, especially towards the eastern region, was driven by the negative wind stress curl which increased towards east. Along the eastern boundary the thick BL was due to a combination of large negative wind stress curl and negative fresh water flux.

In fall intermonsoon the eastward flowing fall-time Wyrтки jet seen during October-November drives the down-welling and sinking of waters along the equator. The excess

precipitation seen from the freshwater flux makes the waters of the equatorial region fresher and the sinking due to Wyrski jet increased the thickness of BL. In contrast, the thick BL seen in northern Bay was driven by the large negative freshwater flux.

In winter the thick BL in the northern Bay was in the region of low salinity ( $< 32.5$  psu) waters and the southward expansion of the region of thick BL was associated with the development of EICC. In November the EICC starts flowing southward from the northern Bay carrying along with it the low salinity waters. During December-January, the EICC flows southward along the western boundary of the Bay transporting the low salinity waters into the eastern Arabian Sea. Thus, the observed spreading of thick BL from the northeastern Bay towards the south along the western boundary and into the west coast of India was driven by the EICC. Along the equator the thick BL during November-December was due to the negative freshwater flux and sinking.

Having deciphered the seasonal variability of the upper ocean, the mixed layer and the barrier layer, the variability of water-column nitrate and chlorophyll *a* were analyzed to understand how they are linked to the upper ocean variability. The nitrate concentrations showed close correspondence with chlorophyll *a* concentrations in the upper ocean. The nitrate concentrations of the upper layer were the least during spring intermonsoon compared to the rest of the seasons. Similarly, the *in situ* chlorophyll *a* as well as the satellite-derived chlorophyll pigment concentrations was also the least varying from 0.1 to 0.2 mg/m<sup>3</sup>. The highest concentrations in spring intermonsoon were along the western boundary. Consistent with this, the chlorophyll *a* concentrations, both *in situ* as well as satellite-derived, were also the least ranging from 0.1 to 0.3 mg/m<sup>3</sup>. The low levels of

nitrate could be understood in the context of prevailing upper ocean conditions. During spring intermonsoon the upper ocean was strongly stratified 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. The observed low chlorophyll *a* concentrations were strongly coupled to mixed layer variability. The nitrate concentrations during summer monsoon were the highest and it occurred in the region of peninsular India and Sri Lanka and near the northern Bay. Accordingly, the chlorophyll concentrations were the highest. The observed high nitrate as well as the chlorophyll *a* concentrations was driven by the upwelling that occurs in the Indo-Sri Lanka region during summer. 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 river runoff supplies nutrients along with sediments and freshwater. 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 inhibits 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, though the nutrient data and *in situ* chlorophyll *a* data were not available, 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. Thus, the observed chlorophyll *a* concentrations in the Bay of Bengal were strongly coupled to mixed layer variability.

It is quite possible that all the characteristics of the seasonal variability of chlorophyll *a* were not fully resolved as the chlorophyll *a* data for any given season was much less in comparison with the nitrate data, both spatially and temporally. Nevertheless, the salient features such as summer monsoon high concentrations in the northern Bay as well as near the Indo-Sri Lanka region, the comparatively high concentrations along the western boundary and the lowest concentrations during spring intermonsoon were all captured.



## Future Work

The research work presented in this thesis was an attempt to understand the basin-scale variability of the mixed layer and then probe into the causative factors that brings about the observed variability using a variety of *in situ* and remote sensing data. The aim of the research was also to understand how these changes in the upper ocean regulate nutrients and chlorophyll in the Bay of Bengal. The study could bring out the role of atmospheric forcing such as heat, momentum and freshwater flux in controlling the mixed layer depth on a seasonal scale. In addition to these local atmospheric forcing, the study also brought out the role of advection of high salinity waters from the Arabian Sea, propagating Rossby waves, and the meso-scale eddies in mediating the changes in the mixed layer depth.

Though the thesis advanced our understanding of the mixed layer variability and its coupling to nutrients and biology in the Bay of Bengal, there is ample scope to explore further. For example, the role of each of the above mechanisms can be determined quantitatively using a physical-biogeochemical model. Another area which needs urgent attention is the generation of quality biogeochemical data. The limitation of this study was the lack of adequate chlorophyll and nutrient data, which did not allow to fully resolve all the characteristics of the seasonal variability.

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