CHAPTER V

THERMOHALINE AND CURRENT VARIABILITY OFF ANDAMAN ISLANDS DURING PRE-MONSOON SEASON
5.1. Introduction

The eastern Bay of Bengal is enriched by a chain of islands emerging from the long range submerged Indonesian Archipelago. These islands are grouped into Andaman and Nicobar Islands. They extend from off Burma to off Sumatra or more precisely, spread between 6°N and 14°N and 91°E and 94°E. The portion of the Archipelago nearer to Burma, consists of extinct volcanoes of which some experience geothermal activity occasionally. These island chains provide a geographic identity to the Andaman Sea. The Andaman Sea is a partially enclosed water body, extending east up to the continental margin of Myanmar, Thailand and Malaysia. It occupies an area of 6.02 x 10^5 km^2 with an average depth of 1096 m. The sea is connected to the Bay of Bengal through several channels between the Islands. Among them three channels viz. (i) Preparis Channel in the north (ii) Ten Degree Channel along 10°N and (iii) the Great Channel in the south are the major ones. The southern Andaman Sea is also connected to the south China Sea through Malacca Strait.

Since the Andaman Sea is a partially enclosed basin and receives copious amount of fresh water from rainfall and river discharge from Irrawady and Salween, this basin exhibits estuarine characteristics with halocline very near to the surface layers (Ramesh Babu and Sastry, 1976). The water body also consists of the watermasses of the south China Sea and of the Bay of Bengal (Ramaraju et al., 1981; Murty et al., 1981). A mixture of these watermasses spread over to the western side of the island groups through several channels and can produce a complicated oceanographic structure there. These island groups are far away from the continental margins and act as a barrier to the free flow of
water bodies. Consequently, modifications in the flow pattern, stratification and mixing are expected in the waters around the Islands. It is well known that the seas around Andaman islands are areas of intense air-sea interaction. There is sufficient evidence for the genesis of the devastating cyclones over the Andaman Sea almost every year (INDIA METEOROLOGICAL DEPARTMENT, 1979; Subbaramayya and Rao, 1981). The complex interaction between the ocean and the atmosphere to trigger the genesis of these cyclones still remains unknown. Being an area under monsoonal influence, the surface winds and currents reverse their directions annually.

Despite all this importance, the studies on oceanographic conditions are very meagre on different spatial (LaViolette, 1967) and temporal scales. The pioneering expeditions covering the physical, chemical, biological and geological aspects, date back to 1913 to 1925 (Sewell, 1925 - 1935). However, after these expeditions, the seas continued to remain unexplored until International Indian Ocean Expedition during 1961 to 1964 (Ramesh Babu and Sastry, 1976; Wyrtki, 1971; Ramesh Babu and Sastry, 1981). During 1979 and 1980, National Institute of Oceanography, Goa conducted a few spatial surveys in the Andaman Sea (Rama Raju et al., 1981; Murty et al., 1981; Sen Gupta et al., 1981). A solitary attempt has been made to assess the short-term variability in the air-sea interaction in the Bay of Port Blair during a 12 h period (Shammi Raj et al., 1990). Some information is available on the thermohaline structure of the western side of the Islands during summer and winter monsoons (Murty et al., 1992; Suryanarayana et al., 1993). Scanty information on the currents is available from the ship drifts (Cutler and Swallow, 1984) and geostrophy (Wyrtki, 1971; Murty et al.,
1981). One study reported the internal solitons in the Andaman Sea (Osborne and Burch, 1980). Apart from the above studies, no information is available, especially on the short-term variability in currents, air-sea interaction and on the other oceanographic and meteorological properties. Thus the oceanographic setting around the Andaman Islands is very important to be probed and studied systematically.

In this chapter, the thermohaline structure around the Andaman Islands is described for a pre-monsoon period. The short-term variability in thermohaline fields, observed subsurface currents, mixing characteristics of the water column and air-sea interaction is studied at a western location off Andamans. An attempt is also made to simulate the ML characteristics using KTDM and NK models.

5.2. Data and methodology

RV Gaveshani covered a saw-tooth track around the Andaman Islands (Fig. 5.1 - dots represent the stations) from 14 to 24 May 1987 to collect data on temperature and salinity in the upper 1000 m/bottom using MICOM STDV (accuracy of sensors: temperature - 0.05°C; salinity - 0.03 PSU; depth - 3 m for 100 m depth). In the STDV, V represents the sound velocity which is not presented in the present analysis. The ship was also anchored at a location off Andamans at 12°28' N and 92°32.6' E (depth 80 m) for three days from 11 to 13 May 1987. During this period, all the standard meteorological data, subsurface salinity and temperature profiles were collected at hourly interval. Five current meters of RCM-4S of Aanderaa make were moored at depths of 3, 18, 33, 45 and 58 m (accuracies of the sensors: speed - 4 cm/s; direction - 5°; temperature - 0.05°C and salinity - 0.03 PSU). The data
were obtained at 5 min interval. Among the data, the temperature at 18 m and salinity at 18 and 58 m depths were found to be unreliable and were not considered for this analysis. The winds were recorded at 14 m height also recorded with an anemograph installed onboard for this cruise, in addition to the hourly observations from the shipborne anemometer.

The overall methods used in this analysis are adapted from Chapter 5.

5.3. Results and discussion
5.3.1. Thermohaline structure around the Islands:

Temperature and salinity distribution around the Islands at different depths (viz. 0, 25, 50 and 75 m) are presented in Fig. 5.1. At the surface, the waters were quite warmer (≈ 31°C) in spite of the sampling covered over seven diurnal cycles (14 to 21 May 1987). These warm water may be one of the favorable factors for the abundant cyclogenesis during May (INDIA METEOROLOGICAL DEPARTMENT, 1979; Subbaramayya and Rao, 1981) in the Andaman Sea. One of the climatological studies shows that the maximum SST (30°C) occurs during May (Wyrtki, 1971). In fact, the SST distribution is bimodal (Wyrtki, 1971; Colborn, 1975) with two maxima occurring during May (30°C) and October (29°C). The minima appear during January-February (26°-27°C) and August-September (27°-28°C). Temperature values higher than 30°C during May were not reported in the climatological studies due to the averaging of scanty data over large spatial and temporal scales. Relatively warmer waters were noticed on the western side of the Island chain at sub-surface levels in conformity with climatology (Levitus,
Fig. 5.1. Temperature and salinity distributions at different depths around the Andaman Islands.
In general, salinity increased from 32.6 to 34.6 PSU from surface to 75 m on the western side. This type of vertical salinity gradient produces stratification in the upper layers. Highly stratified upper layers are a characteristic feature of the Bay of Bengal.

5.3.2. Observations at the stationary location:

Time series of standard marine meteorological parameters at hourly interval are presented in Fig. 5.2. Readings of the shipborne anemometer were reduced to 10 m height (Wu, 1980) for analysis. The atmospheric pressure (PR) showed an overall increase with embedded oscillations of amplitude ~4 mb at semidiurnal period. The wind speed (FF) showed calm conditions with mean speed of ~3 m/s. The cloud cover (CL) varied between 0 and 8 octa. The diurnal heating/cooling events were prominent in dry bulb (DB) and sea surface temperature (SST) data, but were absent in the wet bulb temperature (WB) record. In general, SST was greater than DB during most of the observational period and thus showed a condition for unstable overlying atmosphere.

Estimated heat budget components are presented in Fig. 5.3. As expected for the tropical oceans, the net heat flux (Q) mainly followed the incoming solar radiation (Q_\text{I}). The latent heat loss (Q_\text{E}) was the most dominant heat loss term. Effect of the sensible heat loss (Q_\text{S}) and long wave radiation (Q_\text{B}) was marginal. The diurnal peaks of Q and Q_\text{I} were always >1050 W/m^2 and >1100 W/m^2 respectively.

The effect of the net heat flux on the ner-surface thermal structure can be noticed from the composite plot of temperature profiles. The occurrence of diurnal thermocline
Fig. 5.2. Time series of meteorological elements.
Fig. 5.3. Time series of heat budget components.
extending over the topmost 5 m water column is obvious (Fig. 5.4). This figure shows that the maxima of the isothermal and isohaline layer thickness were 25 m and 30 m respectively. The permanent thermocline was noticed below 25 m depth. The spreading of the isotherms between the depths 10 and 25 m, indicate the influence of the internal oscillations on MLD. Another feature of the temperature profiles was the occasional inversion of 0.2°C to 0.6°C at subsurface layers, especially between 30 and 40 m. Due to the lack of closely sampled spatial data and current meters at closer intervals, the present data set is inadequate to investigate the reasons for these inversions. Inversions of 0.2°C to 0.7°C in the upper layers were found as the characteristic feature of the Andaman Sea (Ramesh Babu and Sastry, 1976; Ramaraju et al., 1981; Murty et al., 1981). Contrary to the variability in the thermal structure, the isohaline layer thickness almost remained constant (~30 m) throughout the observational period. The \( \sigma_t \) profiles mainly followed temperature profiles as expected in the open ocean.

Vertical sections of temperature and salinity are given in Fig. 5.5A to understand their temporal variability at different depths. In the upper 10 m, warmer pockets (>31°C) were noticed due to diurnal heating effect. Below this depth the entire thermal structure fluctuates periodically under the influence of internal tides (periods ~ 12 h) with vertical displacements of 5 to 10 m. Within the thermocline a 20 m layer of weak stratification (~28°C) persists in the depth range of 30 - 50 m.

The salinity structure (Fig. 5.5B) showed diluted layers in the surface (<32.75 PSU) and a progressive increase towards the deeper layers. The oscillations in the isohalines
Fig. 5.4. Composite plot of temperature, salinity and $\sigma_t$. 

<table>
<thead>
<tr>
<th>TEMPERATURE (°C)</th>
<th>SALINITY (PSU)</th>
<th>$\Sigma_t$</th>
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<tr>
<td>22</td>
<td>32</td>
<td>19</td>
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<td>24</td>
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<td>80</td>
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Fig. 5.5A. Depth-time section of temperature.

Fig. 5.5B. Depth-time section of salinity.
also resemble to those noticed in the thermal structure (Fig. 5.5A).

The surface winds recorded on the anemogram were digitized at 10 min interval and were used in the following analysis along with the subsurface current data. The winds at surface and currents at different levels were vectorially averaged and shown in Fig. 5.6A. This figure depicts the mean conditions at the observational site. The wind direction was northeasterly with an average speed around 3 m/s which is not in agreement with the climatological value (Hastenrath and Lamb, 1979). The currents at 3 m depth were almost in the same direction of the wind. But at 18 m depth they changed into westerly direction and thus showed a 90° rotation in the clockwise direction with respect to the current at 3 m. According to the Ekman theory, if the current is fully driven by the local wind, the surface current flow towards 45° right to the wind direction. Also the current vectors should diminish constantly towards deeper layers. In the present observations, the observed mean vectors at 3 and 18 m do not exactly fit into the Ekman Layer. Though the flow at 3 m was southerly, it had changed to westerly at 18 m and to northerly in the thermocline (33, 45 and 58 m). Thus the flow in the thermocline is opposit to the flow near the surface.

The digitized wind and current data are represented as stick plots (Fig. 5.6B) at 10 min interval to understand one to one correspondence. The data were smoothed by an hourly moving average to deduce the low frequency variability clearly. The winds were mostly northwesterly to northeasterly with moderate strength (≈ 5 m/s). The currents in general were stronger in the surface layers (3 and 18 m depths) and were weaker at the below layers (33, 45 and 58 m depths).
Fig. 5.6A. Vectorially averaged surface wind and subsurface currents.

Fig. 5.6B. Stick plots of surface winds and subsurface currents.
During most of the observational period, the surface current (at 3 m) oscillated between south-southeast and south-southwest with peak speeds around 30 cm/s. Although the winds at surface and currents at 3 m depth fluctuated nearly at diurnal and semi-diurnal tidal periods, they were mostly in phase. The currents at 18 m were not the weakest as they seem to be. Since the flow was mostly towards west, the vectors merged with the time axis. Strangely, the flow at the deepest level (at 58 m) was stronger at all the time due to unknown reasons (peak speeds 25 cm/s against 10 cm/s at 45 m and 15 cm/s at 33 m). A common feature among the currents at this site was that their speeds showed a modulation in response to the local internal tides.

Time series plots of temperature (T), salinity (S), east-west component (U) and north-south component (V) at different levels are given in Fig. 5.7 to examine the interrelationship between them. Since the temperature and salinity sensors of current meters had not worked at certain levels, those parameters sampled using MICOM STDV at hourly interval were considered here. The U and V components sampled at 5 min interval were averaged at hourly interval and presented to make compatible with T and S. At 3 m, the dominant oscillations were at semidiurnal periodicity in U and at diurnal periodicity in V. But T was mainly following diurnal heating/cooling cycle only. No particular periodicity was observed in the variability of S. At 18 m, variations in U and V components were mainly at diurnal periodicity with greater amplitude in U. The observed distribution of V at 18 m depth is quite intriguing. Maximum amplitude in the variability of T (≈ 1.5°C) was observed at this level (at semidiurnal periodicity) due to the higher density
Fig. 5.7. Time series of temperature (T), salinity (S) and east-west (U) and north-south (V) components of currents.
stratification between the mixed layer and thermocline. Correlation between currents, T and S were weak from the picture at 3 and 18 m levels. Contrary to the upper two levels (3 and 18 m), the deeper levels exhibited a close relationship between the variability in all the parameters. The most prominent oscillations were at semidiurnal periodicity and also they were in phase each other. However, T showed an inverse relationship with S, U and V. This implied that along with the northerly to easterly currents, the salinity increased and temperature decreased. Since the warmer water was found south of this observational site (Fig 5.1), the decrease in temperature with the increase of V was against the expectations of an increase in T with V. This prompted to believe that the only vertical oscillations due to internal tides were responsible for the decrease in temperature in the thermocline as seen from Fig. 5.5A.

5.3.2.1. Power Spectra: -

The power spectra were computed and presented in Fig. 5.8 to delineate the embedded periodic oscillations in the currents. For the spectral computations, 1024 points at 5 min. interval were used. All the major frequencies were marked at the respective peaks in hours also. Since the actually observed data length was not sufficient, zeroes were padded for deficient number of data points at the beginning and at the end of the zero centred series. As it was noticed from the time series plots (Figs. 5.5A and 5.7), semidiurnal tides were the most occurring periodic oscillations in the spectra of all the parameters. This showed the dominance of semi-diurnal tides at the observational area which is in agreement with the observations reported and discussed in
Fig. 5.8. Spectra of temperature (T), salinity (S), and east-west (U) and north-south (V) components of currents.
Chapters III, IV and V. The other most frequently occurring harmonic was 28.4 h. This might be due to the diurnal wave of 24 h periodicity. Since the resolving periodicity on both sides of 24 h are 21.3 h and 28.4 h, 24 h periodicity reflects either in 28.4 h or 21.3 h only. The diurnal heat wave was dominating over the semi-diurnal tidal oscillation in temperature at 3 m. But the heating effect had considerably decreased at 33 m and was absent at the other lower depths. The shape of all the spectra were more or less similar except those of 'S' at 3 m and 'V' at 18 m. This indicates that the causative factors for the periodic oscillations of these factors were different compared to those of the other parameters at other levels. The variability in S might have been aperiodic as it was revealed from time series plot (Fig. 5.7). The currents at 18 m came under the shearing zone (Fig. 5.6) of southerly flow near the surface (3 m) and northerly flow at 33 m depths. So the opposing flow in the meridional direction at either levels might have influenced and dampened the natural frequencies at 18 m resulting in a different shape of spectra.

5.3.2.2. Mixing Characteristics of the water column:-

Hourly temperature and salinity data collected by MICOM STDV and vectorially averaged current data at hourly intervals were used to make time series (Fig. 5.9) of Richardson Number (Ri), Brunt Vaisala Frequency (N) and vertical shear (SR) for different layers. The N widely fluctuated between 0 and 9 c.p.h. in the upper slab (3 to 18 m). But the range of variation was less (~5 c.p.h.) in the middle and bottom layers where the values were always higher than 8 c.p.h. The higher fluctuation in the surface layers
Fig. 5.9. Time series of Richardson number (Ri), Brunt Vaisala Frequency (N) and vertical current shear (SR).
was due to the oscillation of the pycnocline at the interface of the mixed layer and pycnocline. The SR was relatively higher (0.005 to 0.02 S\(^{-1}\)) in the upper slab compared to that of below layer slabs (0 to 0.01 S\(^{-1}\)). The relative importance of \(N\) and \(SR\) on \(R_i\) are discussed below. The \(R_i\) fell below 0.25 on three occasions which was conducive for instability in the upper slab. The lowest \(R_i\) occurred at night on all days when \(N\) was small. This observation proved that the instability in the upper slab had occurred due to very weak vertical density gradient during night followed by a deeper mixed layer. It is interesting to note that the deepening of mixed layer had occurred due to the intrusion of warmer water between 10 and 25 m and the disappearance of diurnal thermocline with in the upper 10 m (Fig 5.4 and 5.5A). This feature is contrary to that of the other oceanic regions where the deepening of MLD during night is generally only due to cooling in the mixed layer. At this stage, it is useful to refer Fig. 5.7 again. Only diurnal component was most prominent in \(V\) component at 3 m and in \(U\) and \(V\) components at 18 m. Also the period of occurrence of the higher peaks in them coincided with the spells of instability in the upper slab. This proved that during the night time, the northerly currents were primarily responsible for the maintenance of higher temperature (>30.5°C) at the upper slab. This inference was in agreement with the general distribution of temperature (Fig. 5.1) in which warmer water was observed in the southern region. Thus it can be concluded that in the upper 25 m, horizontal flow at diurnal periodicity was one of the major factors controlling the thermal and mixed layer characteristics. However, this inference is against that of in the thermocline (Fig. 5.5A)
where the vertical oscillations of semi-diurnal periodicity were found as the controlling factor. Thus it has proved the relative influence of horizontal currents and vertical oscillation of internal tide on the variability of the thermal field in the mixed layer and thermocline respectively. The Ri at the other 3 slabs (18-33, 33-45 and 45-58) was always higher than the critical value which showed stable layers throughout the observational period.

5.3.2.3. Simulation of the mixed layer characteristics:

Simulation of the mixed layer characteristics (Fig. 5.10) was done following the methodology used in the Chapter V. Values of \( m_1 \) and \( m_2 \) in NK were found more appropriate when they were 0.39 and 0.8 respectively (a combination from Davis et al., 1981). The best simulation with KTDM was obtained when the value of '\( \gamma \) ' and \( m \) was assigned 0.00085 and 0.009 respectively. The observed MLD fluctuated in a wide range between 5 and 25 m. The shallowest MLD occurred in the afternoon due to heating whereas the deepest MLD occurred during night time due to the intrusion of warmer waters at the subsurface layers (5.3.2.2). Time series of MLD, showed the dominance of other oscillations also. But, the observed MLT showed only one dominant periodic oscillation of diurnal heating/cooling cycle. The shoaling and heating events were simulated reasonably well by both the models. But some improvement can be seen in the case of NK. The deepening events could not be simulated by both the models. However, the amplitude of diurnal heating cycle were better reproduced by the MDKT model. From Figs. 5.3, 5.4 and 5.5A, the response of the near surface layers to the net heat flux was clearly revealed. Therefore, the present models driven by net
Fig. 5.10. Time series of mixed layer depth (MLD) and mixed layer temperature (MLT).
heat flux, performed well for the heating events. But it is seen from the Chapters IV and V that the parameterization for the solar absorption in the sea is better in NK than that of KTDM. Hence the simulated heating maxima were better with NK model. It is concluded in the section 5.3.2.2, that the deepening event had occurred due to the intrusion of warmer water during night time at diurnal periodicity at the subsurface layer (between 10 and 25 m). This process is not incorporated in the present models. Consequently wider departure between the observed and predicted values is noticed. The intrusion of warmer water maintained comparatively higher temperature during night time also. Therefore, it is to be expected simulated temperatures with the one dimensional models would be warmer. Considering this fact, NK seems to be more acceptable model eventhough the KTDM produced better matching during the cooling regime between the predicted and observed MLT. In short, this study also necessitates a comprehensive study of internal processes around Andaman Sea, as it is seen in Chapter V.