Structure of the oceanic mixed layer in western Bay of Bengal during MONEX*

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ABSTRACT. Based on the hourly BT and six hourly CSTD data, collected from two stations in the western Bay of Bengal during July 1979, the diurnal variations of temperature in the oceanic mixed layer (OML) were analysed as a function of the prevailing surface layer conditions of the overlying atmosphere. Structure of OML, as delineated with respect to the diurnal variation of temperature with depth, revealed three sub-layers: wave mixed, diurnal thermocline and transition layer. The first two sub-layers of OML showed immediate responses to the changes in surface meteorological forcings. Surface were mixing, convective activity and internal waves were found to be the main physical processes to effect the thickness of wave mixed, diurnal thermocline and transition layer respectively.

1. Introduction

One of the major objectives of MONEX is to examine the coupling between the atmosphere and ocean. This coupling at the sea surface is mainly through two boundary layers (BLS), viz., surface layer (SL) of the atmosphere and oceanic mixed layer (OML) (Sarachik 1977). These two BLS have great roles in the dynamics and thermodynamics of surface and upper air circulations. Considering this importance, the SL conditions of atmosphere over the western Bay of Bengal during MONEX have been studied (Anto et al. 1982) for the three different synoptic scale circulations that prevailed during the period of observations. Studies on the structure of OML, for the same period and region, are important for understanding the different aspects of the coupling mechanism because the upper layers of ocean significantly influence the surface meteorological forcing and vice versa. In the present study the diurnal variations in temperature and the resulting structure of OML, were analysed as a function of the prevailing SL conditions of atmosphere over western Bay of Bengal during July 1979.

2. Materials and Methods

During the sixth MONEX cruise of R.V. Gangesari the MBT/XBT at hourly intervals and CSTD data at six hourly intervals were collected from two stations (Fig. 1): 13° N, 85° E (Station A) and 16° N, 87° E (Station B). The oceanographic and surface meteorological observations were selected for the full day period of 20-22 July at Station A and 25-30 July 1979 at Station B. The BT data was checked with the temperature data available from the CSTD profiles. The weak temperature variations in OML, as observed from the MBT/XBT and CSTD data, motivated for the determination of the amplitude of diurnal variation of temperature through harmonic analysis. The amplitudinal variation of temperature with depth was adopted as the criteria here for delineating the layered structure of the weakly stratified OML. The diurnal variations in the structure and thickness of OML were compared with diurnal variations of sea-air temperature difference (SADT), wind stress and convective activity in SL (Anto et al. 1982). In the present study the weakly

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stratified OML was demarcated from the strongly stratified thermocline for a temperature of 1°C less than the surface value (Colburn 1974).

3. Results and discussion

3.1. Atmospheric surface layer

The SL conditions of atmosphere over western Bay of Bengal during July 1979 were characterised by the veering and backing effects of surface winds. Based on the present weather (ww) conditions, surface meteorological data from Station B from two groups, viz., GI and GII. Thus the available surface meteorological data from Stations A and B represent three periods, i.e., 20-22 July at Station A, 25-27 July at Station B (G1), and 28-30 July 1979 at Station B (GII). These three periods, characterised by anticyclonic (Station A), precursor anticyclonic (GI) and cyclonic (GII) circulations in SL, will account for three different conditions of ww, atmospheric pressure, sea surface temperature (SST), etc. Air temperature and pressure were higher at Station A than that during GI and GII. The relatively warmer sea surface during GI reflects the precursor situation for the formation of cyclonic circulation. The low SST observed during GII appears to be the result of evaporative cooling by strong surface winds. Another important feature observed in SL is the convective activity which is low at Station A and high during GII. These surface meteorological conditions at Stations A and B (GI & GII) were compared (Anto et al. 1982) to highlight the varying SL features under three different synoptic weather conditions. Averaging over the three-day period is sufficient to elucidate synoptic scale diurnal variations in the SL and OML which are mainly controlled by the energy exchange processes at the air-sea interface.

3.2. Diurnal temperature variations in OML

The diurnal variations of temperature in OML were analysed in terms of the studies on SL (Anto et al. 1982) for the same periods. Station A, GI & GII. Air temperature variation with depth is a good indicator of stability, the weak diurnal thermal stratification in OML and the temperature deviations (Hasse 1971) in the upper layers of OML were analysed as a function of the prevailing SL conditions. Like air circulation, wind stress variations, SST, convective activity etc. The diurnal temperature variations (Figs. 2, 3, 4a) and the mean diurnal temperature variations (Fig. 5) showed weak stratifications in OML. These three figures show that the diurnal temperature variations in the three cases represent for the three different conditions. The internal wave activity is also seen in the transition layer between weakly stratified OML and strongly stratified thermocline. Thus OML was found to be weakly stratified by different SL conditions, day time heating and night time cooling at the surface and internal wave activity at the bottom. The mean diurnal variation of surface temperature at Station A and during GI and GII was of the order of 0.3°C. Higher values were observed on 25th and 28th (0.9°C-0.4°C) when the SL circulations changed to precursor and cyclonic conditions. This signified the role of ww on the diurnal variation of surface temperature. During the precursor circulation of GI, there was a temperature inversion in the surface layers (Fig. 3b). The fall of surface temperature around 0620 hrs of 28th (Fig. 4b) was followed by the onset of cyclonic circulation. During GI, sea surface was relatively warmer than that at Station A and GI (Anto et al. 1982). The relatively warmer SST during the precursor SL circulation of GI and the colder SST during the cyclonic SL conditions of GII indicate the immediate response of SST to the prevailing ww changes in SL. Earlier studies (Shukla & Mśra 1977) also show that the response of the surface layers to the cyclonic storm is to make the surface layers warmer, as seen during GII, because of the heat loss to the atmosphere, due to vertical and horizontal heat advection and turbulent mixing. According to La Fond (1954), the predominant external environmental factors to produce or eliminate the vertical temperature gradients in OML are the energy transfer processes at the air-sea and the advective transfer processes below the sea surface. The diurnal march of temperature in OML could be seen from the temperature profiles of CSTD records (Figs. 2, 3, 4b). The common features of diurnal heating and cooling effects were seen at Station A and during GI. The warmer sub-surface cells on 20th (Fig. 2a) around 1400 hrs mixed down to a depth of about 25-45 m. The upper warmer layers of OML at these two stations were almost stable, suppressing the downward wind mixing. In contrast, the thermal structure of OML (Figs. 4a & 5c) showed the colder layers over warmer ones, appearing to cause instability and convective mixing, during GII.
Figs. 2 (a & b). Diurnal variation of: (a) Temperature from MBT/XBT data, & (b) Temperature, $S(^\circ/\text{oo})$ and $\sigma_f$ from CSTD data.

Figs. 3 (a & b). Diurnal variation of: (a) Temperature from MBT/XBT data, & (b) Temperature, $S(^\circ/\text{oo})$ and $\sigma_f$ from CSTD data.
3.3. Salinity and density variations

Another factor that controlled the OML stability was the salinity. The observed features of diurnal variations in the salinity are given in Figs. 2, 3 & 4(b). At Station A and GI, there was little salinity gradient in the OML. The instantaneous positive salinity gradient in the surface was present during GI1 (as seen on 28th at a depth of 10m) because of the rain (w=02, 13, 21, 50 and 60) (Anto et al. 1982) associated with the cyclonic circulation. The sudden salinity variations in surface layers obscure (worthem & Ostagoff 1976) the diurnal heating effects. This also contributed to lower the temperature of the surface layers as seen during GI1. The resultant effects of temperature and salinity on stability could be seen from the $\sigma_t$ variations which are mostly of neutral nature (Figs. 2, 3 & 4 b).

### Table 1

<table>
<thead>
<tr>
<th>Station A</th>
<th>Station B</th>
<th>GI</th>
<th>Station B-GI1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oceanic mixed layer thickness (m)</td>
<td>55</td>
<td>70</td>
<td>75</td>
</tr>
<tr>
<td>Wind stress (dynes/cm²)</td>
<td>1.229</td>
<td>0.554</td>
<td>2.477</td>
</tr>
<tr>
<td>Wave mixed layer (m)</td>
<td>5</td>
<td>5</td>
<td>7</td>
</tr>
<tr>
<td>Diurnal thermocline layer (m)</td>
<td>40</td>
<td>55</td>
<td>55</td>
</tr>
<tr>
<td>Transition layer (m)</td>
<td>10</td>
<td>10</td>
<td>13</td>
</tr>
</tbody>
</table>

3.4. Thickness of OML

As a consequence of these diurnal temperature variations, the OML was thicker during GI1 than the other two cases — Station A and GI (Fig. 7a). The mean values of OML thicknesses are given in Table 1. The variations in OML thicknesses during the three periods (Station A, GI and GI1) showed resemblances to the trend of the SATD variations (Fig. 7b) and appeared to be independent of the wind stress effects (Fig. 7c) which extended only to the upper layers of OML. SATD values were low at Station A and comparatively high during GI1. The SATD indications confirmed the coupling mechanism at the navicface and implied that the temperature variations at the navicface were significant in the physical processes that controlled the depth of OML. For example, in Laevsuttu’s model for the depth of mixing by waves, the significant wave height is formulated with the SATD (Geary 1961). The cyclonic effects appeared to contribute for the deepening of OML. As explained earlier (Anto et al. 1982), the three periods (Station A, GI and GI1) of observations are considered to represent three different synoptic scale circulations in SL. Hence, the mean values of Table 1 are meant for the different w and the latitudinal variations in OML are not dealt with.

3.5. Layered structure of OML

Because of the different environmental factors, as mentioned above, OML was generally composed of layers of different temperatures, characterized by different physical processes like heating, cooling, mixing, advection, etc. OML can be divided into three sub-layers, viz., wave mixed layer (WML) at the surface, diurnal thermocline layer within the OML and the transition layer at the bottom of OML (worthem & Ostagoff 1976; Ostapoff & Worthem 1974; Garstang
& Betts 1974). A schematic representation of these three sub-layers is given by Worthing and Ostapoff (1976). SATD at the naviface, wave mixing in the WML, diurnal heating in the diurnal thermocline layer and internal waves breaking in the transition layer were the main physical processes to affect the characteristics of the sub-layers. These significant physical processes require further detailed investigations by refining the accuracy of temperature measurements.

(a) Wave mixed layer

The average WML thickness at Station A and during G1 and GI1 were found to be approximately 5 m (Table 1) and a larger value of 15 m was observed on 22 July. The WML thickness on 26, 27, 29 and 30 July was about 10 m (Fig. 6). The WML values from Fig. 6 were compared with the computed values of thickness of WML (Δ) when the wind speeds were low (Station B-G1). Such a computation was required to compare with the linearly extrapolated values. The average computed values of Δ was about 7 m. In the surface layer, the effect of waves extends to a depth of Δ (thickness of WML) which equals the wave length associated with the peak of the surface wave energy spectrum (Pierson 1964). The approximate wave length, Δ, of the dominating surface waves is given by Augstein Δ = 0.3 U², where U is the wind speed. At Station A and Station B-G1, WMLs were conspicuous, whereas during G1, the upper layers constituted a sudden fall in amplitude causing uncertainty to determine the thickness of WML. Hence, the linear extrapolation method (Colburn 1974) was adopted to distinguish the WML during G1. The extrapolation method to demarcate the OML from thermocline is reasonable because of the large temperature gradient prevailing in the transition layer. Even though, such a large gradient may not prevail between the WML and diurnal thermocline layer, some large variations in the temperature amplitude at Station B-G1 could be expected because of the transition stage (precursor anticyclonic) between anticyclonic and cyclonic circulations. The three different thermal structures of OML (Fig. 5) account for the effects of different SL meteorological forcings.

(b) Diurnal thermocline layer

The average thickness of diurnal thermocline layer in the three cases are given in Table 1. Compared to G1 and GI of Station B, Station A showed large variation of temperature in the diurnal thermocline. As
mentioned above, Station A experienced both day time heating and night time cooling on 21 and 22 July, whereas surface layers showed only the cooling trend on 20 July. This led to the weak warmer cells and weak convective mixing as seen on 20 July (Fig. 2a). During G1 and G11, diurnal thermocline layer was almost isothermal, because the precursor and cyclonic effects mainly controlled the thermal structure. Warmer surface and sub-surface layers of G1 were in agreement with the precursor conditions of the sea. The colder surface layers over warmer cells (G11), a characteristic feature during cyclonic condition, might cause instability and convective mixing. The convective mixing appears to be the major physical process in controlling the thickness of diurnal thermocline layer, which was also subjected to the entrainment effects from the transition layer.

(c) Transition layer

The thickness of the transition layer was found to be equal at Station A and G1 (Table 1). During G11, the mean thickness of transition layer was slightly higher. Further, G1 showed less variations in layer II (Fig. 6). It appeared that these variations were related to the effect of convective mixing which controlled the weak and active entrainment effects of internal waves at the boundary of OML and thermocline. The presence of higher SST and colder sub-surface layers reduced the convective mixing in the diurnal thermocline layer at Station B-G1.

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