Mixed layer height over Bay of Bengal during Indian summer monsoon using MONTBLEX observations

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The height of mixed layer and cloud base is studied in relation to surface meteorological parameters, surface fluxes of heat and momentum and synoptic weather disturbances. For this study, surface as well as upper air meteorological observations collected over north Bay of Bengal (20°N, 89°E) during the summer monsoon of 1990 as a part of Monsoon Trough Boundary Layer Experiment (MONTBLEX), were utilized. Empirical relation between the cloud base height and the surface meteorological observations has been verified for its validity over Bay of Bengal. This height is further compared with aerological observations. A simple relation based on surface air temperature, pressure and wind speed has been suggested to estimate the cloud base height. Influence of the turbulent surface fluxes of heat and momentum on evolution of mixed layer over Bay of Bengal has been brought out.

Keywords: MONTBLEX, Bay of Bengal, Virtual potential temperature, Mixed layer height, Cloud base height, Surface fluxes.

1 Introduction

Studies on the characteristic features of the marine boundary layer are important for understanding the heat and moisture budget of the boundary layer. Convective boundary layer (CBL)/mixed layer height determines the vertical transport and diffusion of pollutants in the atmospheric boundary layer (ABL). Passive quantities such as particles and gases are mixed nearly uniformly throughout the layer by turbulence which results partially from strong surface heating during the daytime hours. The mixed layer is capped by a temperature inversion which impedes entrainment of air from above into that below, thereby limiting the height of mixing. Over land, the extent of the mixed layer largely depend upon the heat received by the earth surface, but over ocean, the latent heat flux along with the sensible heat flux determines the characteristic structure of the sub-cloud layer. Thus, variation of the mixed height depends on solar radiation, synoptic conditions and local terrain.

It is known that tropical weather systems over oceans are strongly dependent on air-sea exchange processes. The development of these processes depends upon the atmospheric conditions and the state of the underlying sea-surface. Over a uniform ocean, the sub-cloud layer is cooler than the ocean because of the radiative cooling. This creates the instability in the surface layer and maintains the heat fluxes (viz. sensible and latent). As far as the moisture balance is concerned, the upward moisture flux at the surface balances the subsidence of dry air. The resulting equilibrium moisture structure and associated cloud fields play an important role in the heat budget. Recent studies relating the surface fluxes of heat and momentum showed that these fluxes have increased steeply during the period of disturbances over the north Bay of Bengal.

It is understood that the boundary layer processes are basically associated with the fluxes in that layer where wind speed plays an important role. In many formulation used in the estimation of mixed layer/cloud base height, more emphasis has been given to the convective parameters. Hence, in the present study the first aim is to bring out the significance of the wind speed in the computation of mixed layer/cloud base height where both the convective as well as dynamic parameters can be considered. The second aim is to check the importance of surface fluxes of heat and momentum on the evolution of mixed layer over Bay of Bengal. Further, the sensitivity of cloud base height on air temperature and SST has been tested.

2 Location of observations and meteorological conditions

Monsoon Trough Boundary Layer Experiment
(MONTBLEX) was the first experiment conducted to study the boundary layer processes in the monsoon trough regions. This experiment was conducted in the summer monsoon season (June-September) of 1990. As a part of MONTBLEX, the surface meteorological observations along with radiosonde ascents were taken onboard Oceanographic Research Vessel 'Sagarikanya' in the north Bay of Bengal (20°N, 89°E). The three-hourly surface observations, viz. sea surface temperature (SST), dry bulb temperature, wet bulb temperature, winds, etc. were collected. Low level radiosonde, specially designed for this experiment, were used to obtain data accurately at shorter intervals by giving less rate of ascent (6-7 km/hr). The vessel was moored at the location (20°N, 89°E) in the north Bay of Bengal for the entire observational period, i.e from 18 Aug. to 19 Sep. 1990. These observational data were supplied by National Institute of Oceanography, Goa.

The period of 20-25 August is marked with the formation of deep depression centred in the north Bay of Bengal. During 28-31 August, the monsoon trough was shifted towards the south of its normal position heralding rainfall activity in the central part of India. A depression was also formed during 1-4 Sep. 1990 near the eastern part. Eastern part of the monsoon trough shifted from Nepal to north Bay of Bengal during 6-8 Sep. 1990. Synoptic meteorological observations and weather conditions during the MONTBLEX is critically and thoroughly discussed by Srivastav.

3 Profiles of virtual potential temperature

Profiles of potential temperature is used to determine the mixed layer height. Potential temperature and humidity are nearly constant with height in the mixed layer. Top of the convective mixed layer is the level of most negative heat flux and is at the height where the capping inversion is strongest. Another measure of the average mixed layer depth is the height at which an undiluted air parcel rising from the surface becomes neutrally buoyant. Potential temperature is minimum near the middle of the mixed layer, because heating from below and entrainment of warm air from above leads to slightly warmer potential temperature in these regions. However, moisture often decreases slightly with height, because surface evaporation is adding moisture below, while entrainment of dry air is occurring at the top of the mixed layer.

During MONTBLEX, the radiosonde ascents were taken at 0000 and 1200 hrs GMT. On a few occasions (23, 25 August and 12 September), radiosonde ascents at 0600 hrs GMT were available. Over the north Bay of Bengal, during the observational period, the observed virtual potential temperature ($\theta_v$) profiles can be grouped in three categories. First, the constant $\theta_v$ throughout the boundary layer [Fig.1(a)]. Secondly, the $\theta_v$ profile was divided into the sections of inversion (stable) from surface, and unstable-to-neutral conditions above this [Fig.1 (b)], and finally few profiles have constant $\theta_v$ (neutral conditions) in the upper

![Profiles of virtual potential temperature](image)

**Fig. 1**—Profiles of virtual potential temperature on (a) 28 Aug.: 1200 hrs GMT (b) 18 Aug.: 1200 hrs GMT and (c) 25 Aug.: 0600 hrs GMT; 1990.
determination in the former is the height another is the 1 temperature of potential moisture surface strained mixed

part (950-875 mbar) of the ABL and inversion layer in the surface [Fig. 1 (c)]. Constancy of $\theta_v$ profile was considered to estimate a mixed layer height. When the $\theta_v$ profile consists of three types of stability regimes [i.e. some part of ABL as unstable, some part as inversion (highly stable) and remaining part as constant $\theta_v$ (neutral conditions)], then in such cases the rising parcel methodology\(^7\) was followed to estimate the mixed layer height. In cases of inversions, it is difficult to detect the mixed layer height.

4 Mixed layer height as a cloud base height

The monsoon trough is the seat of cyclonic vorticity in the lower troposphere, particularly, in the eastern end of monsoon trough (over the north Bay of Bengal) where organized moist convection prevails during the monsoon months. In this region the upward motions carry boundary layer air away from the ground to large altitudes throughout the troposphere. In these situations, it is difficult to define the boundary layer top. In these cases, cloud base is often used as an arbitrary cut-off for boundary layer studies. In order to get the cloud base height with available observations, the following empirical formula as suggested by Betts and Ridgway\(^1\) has been used.

$$P_B = P_0 - 390 \cdot \frac{1.0 + 0.35(300 - T_0)}{V_0} \quad \ldots (1)$$

where

- $P_B$ = Pressure at cloud base (mbar)
- $P_0$ = Surface pressure (mbar)
- $V_0$ = Surface wind velocity (ms\(^{-1}\))
- $T_0$ = SST (K)

Equation (1) gives the cloud base height using relationship between the surface pressure, SST and surface wind. The main advantage of the above formula [Eq. (1)] over the traditional formula\(^3\) for cloud base height (lifting condensation level) is that the latter does not take into account the surface wind speed.

The cloud base height estimated using Eq. (1) is compared with that of mixed layer height observed by the radiosonde ascents. This comparison is shown in Table 1. Table 1 shows that the values compare well with each other and are reasonable. This suggests that the cloud base height can be approximated to mixed layer height during the monsoon conditions over the Bay of Bengal.

5 Variation in cloud base height

Betts and Ridgway\(^1\) explored the role of surface wind speed along with SST and cloudiness in the energy balance over the tropical oceanic region. As the wind speed changes, the moistening of the subcloud layer due to surface evaporation also changes affecting the SST. The observed SST, cloud amount and wind speed along with cloud base (CB) height are shown in Fig. 2 [(a)-(d)] for the periods 18 August-1 September and 8-19 September. Observations were not available during 2-9 Sep. 1990. In the Fig. 2 (d), the CB height show synoptic scale variation. Also in undisturbed period, diurnal variation in CB height is seen. During disturbed period, the CB height was minimum. During the undisturbed conditions, evolution of mixed layer depend on the surface heating which has a diurnal characteristics. However, during disturbed conditions, increase in cloudiness reduces the surface heating which disturbs the diurnal characteristics of heat. These characteristics were also supported by the studies of the mixed layer over Arabian Sea during Monsoon Experiment (MONSOON-77) which showed that the diurnal characteristics were less pronounced during the disturbed period, whereas it was much pronounced in the undisturbed period\(^6\).

During disturbed period, there was an increase in surface wind which was found to be associated with the decrease in SST and increase in low cloud amount. Betts and Ridgway\(^1\) showed the relationship between SST, surface wind and cloudiness. With the increase in wind speed, the SST has shown a decrease. The surface wind is responsible for forcing the

### Table 1—Comparison of mixed layer (ML) and cloud base (CB) height

<table>
<thead>
<tr>
<th>Date (1990)</th>
<th>Time hrs GMT</th>
<th>ML height mbar</th>
<th>CB height from Eq. (1) mbar</th>
</tr>
</thead>
<tbody>
<tr>
<td>23 Aug.</td>
<td>06</td>
<td>900</td>
<td>886</td>
</tr>
<tr>
<td>23 Aug.</td>
<td>12</td>
<td>926</td>
<td>939</td>
</tr>
<tr>
<td>28 Aug.</td>
<td>12</td>
<td>907</td>
<td>929</td>
</tr>
<tr>
<td>29 Aug.</td>
<td>12</td>
<td>905</td>
<td>921</td>
</tr>
<tr>
<td>30 Aug.</td>
<td>00</td>
<td>921</td>
<td>913</td>
</tr>
<tr>
<td>30 Aug.</td>
<td>12</td>
<td>890</td>
<td>881</td>
</tr>
<tr>
<td>1 Sep.</td>
<td>00</td>
<td>810</td>
<td>823</td>
</tr>
<tr>
<td>1 Sep.</td>
<td>12</td>
<td>840</td>
<td>824</td>
</tr>
<tr>
<td>8 Sep.</td>
<td>12</td>
<td>910</td>
<td>901</td>
</tr>
<tr>
<td>12 Sep.</td>
<td>06</td>
<td>785</td>
<td>760</td>
</tr>
<tr>
<td>13 Sep.</td>
<td>12</td>
<td>910</td>
<td>912</td>
</tr>
<tr>
<td>14 Sep.</td>
<td>12</td>
<td>902</td>
<td>916</td>
</tr>
<tr>
<td>18 Sep.</td>
<td>12</td>
<td>850</td>
<td>822</td>
</tr>
</tbody>
</table>
Fig. 2—Diurnal variation of (a) SST, (b) Cloud amount, (c) Wind speed and (d) Cloud base height for the period 18 Aug.-1 Sep. and 8-19 Sep., 1990.
surface evaporation. At low wind speed, the mixed layer dries rapidly and SST increases sharply.

The inverse relationship between the wind speed and cloud base level was observed as suggested by the Betts and Ridgway\(^1\). During disturbed period, high values of winds were associated with the decrease in CB height or increase in cloudiness. Deep convective clouds play an important role in injecting mass into the boundary layer in the form of convective down-drafts. The downdraft-injection usually consists of dry and cool air and can be accompanied by locally gusty winds. So, they tend to lead enhanced surface fluxes\(^10\). A given upward surface sensible heat flux can rapidly increase the temperature of the shallow boundary layer where the same flux will warm up a deep boundary layer slowly. Due to warming, the surface fluxes reduce and hence the shallow boundary layer has weak surface fluxes, while a deep boundary layer can have much stronger fluxes.

Analogous to the formula of Betts and Ridgway\(^1\), the following formula is tested for the estimation of CB height over the Bay of Bengal region.

\[
P_B = P_0 - 390 \cdot \frac{1.0 + 0.35 (300 - T)}{V_0}
\]

where, \(T\) is the air temperature at deck level. In Eq. (2), the air temperature is considered instead of SST. This has been done because of the difficulties in measuring SST. The comparison of estimated CB height using Eqs (1) and (2) is shown in Fig. 3.

6 Dependency of mixed layer height and surface fluxes

It is understood that the surface fluxes of heat and momentum play an important role in the evolution of boundary layer over the land surfaces. The surface fluxes of sensible heat, latent heat and momentum were estimated using the profile method based on Monin-Obukhov similarity theory by assuming a roughness length of 2 mm over Bay of Bengal\(^11\). The gradient between SST and air temperature, and wind speed (at only one height) combined with roughness length were used to compute the similarity functions\(^12\). Numerical iteration method\(^13\) was used to compute frictional velocity \(u^*\) scaling temperature \(\theta\) and scaling humidity \((q_v)\). The surface fluxes of sensible heat \((H)\), latent heat \((E)\) and momentum \((\tau)\) were estimated using following relations.

\[
H = -\rho C_p \theta u^*
\]

\[
E = -\rho L_v q_v u^*
\]

\[
\tau = -\rho u^*^2
\]

where, \(L_v\) is the latent heat of water vaporization, \(C_p\) the specific heat at constant pressure and \(\rho\) the density of air. Details on the profile method and procedure of iteration are given by Bercowicz and Prahm\(^13\).

Over the ocean surface, the boundary layer height is generally determined by the strength of wind stress and the sensible heat flux. Additionally, in the ocean region which is close to the land, the presence of dry continental air-masses at higher altitudes may also influence the mixing process and contribute to the growth of boundary layer. The dependence of boundary layer height with respect to momentum, sensible heat and latent heat fluxes are given in Fig. 4 [(a)-(c)]. It is observed that mixed layer height depends weakly on the fluxes of sensible and latent heat, but it moderately depends on momentum flux. A lot of variations in mixed layer height were observed for the momentum flux less than 0.03 N m\(^{-2}\). For the higher momentum flux, the mixed layer height appears to be approximately constant at 920 to 900 mbar.

Results from the recent study of marine boundary layer over Indian ocean also showed the dependency of mixed layer height on surface fluxes in the southern hemisphere\(^14\). However, the same study suggests that in the northern hemisphere, the mixed layer height does not depend on the surface fluxes alone. This corroborate the results of the present study.

7 Summary

Virtual potential temperature profiles obtained from the meteorological observations collected during MONTBLEX, in the vicinity of the depression/low
pressure systems showed different characteristics. The meteorological parameters (SST, wind speed and pressure) showed synoptic scale variation. The empirical relations for the CB height given by Betts and Ridgway\(^1\) were tested against the height of mixed layer and they showed good agreement over the Bay of Bengal during monsoon conditions. This suggested that CB height and mixed layer height can be treated nearly equally during the monsoon conditions over Bay of Bengal. The CB height showed diurnal variation during undisturbed period when the cloud amounts were low. The dependency of mixed layer height with respect to turbulent fluxes in the surface layer was found to be poor.

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**References**