MAUSAM, **54**, 2 (April 2003), 529-538

551.510.522

Structure of the convective boundary layer - A method to delineate the sub layers

SAVITA B. MORWAL

Indian Institute of Tropical Meteorology, Pune - 411 008, India

(*Received 3 January 2002, Modified 17 May 2002*)

सार – इस शोध–पत्र में ग्रीष्मकालीन मानसून ऋतु के दौरान उत्तरी हिंद महासागर के क्षेत्रों में संवहनी परिसीमा सतह में विभिन्न प्रकार की उपसतहों को वर्णित करने की विभिन्न पद्धतियों को प्रस्तुत किया गया है। उपर्युक्त पद्धति की उपयोगिता को सिद्ध करने के लिए अरब सागर (चरण I ए और I बी), हिंद महासागर में भूमध्यरेखा (चरण II) और बंगाल की खाड़ी (चरण III) के क्षेत्रों में जून–अगस्त 1977 के दौरान किए गए मानसून–77 के प्रयोग से प्राप्त किए गए सभी उपलब्ध आंकड़ा सेट (केवल वायुविज्ञानीय प्रेक्षणों) पर विचार किया गया है।

संवहनी परिसीमा सतह की उर्ध्वाधर संरचना से चार स्तरीय संरचनाओं अर्थात् पृष्ठीय स्तर, उप मेघ स्तर, मेघ स्तर और कैपिंग स्थायी स्तर का पता चला है। इन स्तरों को संतृप्ति दाब कमी (पी*, हैक्टापास्कल) और मिश्रित प्राचल (β, अविम) के औसतन उर्ध्वाधर प्रोफाइलों का प्रयोग करते हुए एक दूसरे से पृथक किया जा सकता है। उच्चतम सी.बी.एल. को पी* के न्यूनतम मान द्वारा स्पष्ट किया गया है। इस अध्ययन से यह पता चला है कि सामान्यतः उत्तरी हिंद महासागरीय क्षेत्रों में सतह और उप मेघ स्तर क्रमशः 1000 हैक्टापास्कल और 950 हैक्टापास्कल तक फैले हुए हैं। इसमें यह भी पता चला है कि I ए, I बी, II और III चरणों के दौरान मेघ स्तर की गहनता में भिन्नता पाई गई है। इस दौरान की गई जाँचों से यह पता चला है कि पोतों पर सभी तीन चरणों के दौरान सी.बी.एल. की गहनता 650 हैक्टापास्कल तक पाई गई है।

ABSTRACT. The paper introduces a different method to delineate the different sub layers in the Convective Boundary Layer over the north Indian Oceanic regions during the summer monsoon season. The all available data set (only aerological observations) from the MONSOON-77 experiment during the June-August 1977 over the Arabian Sea (Phase IA and IB), Equatorial Indian Ocean (Phase II) and Bay of Bengal (Phase III) regions have been considered to demonstrate the usefulness of the above method.

The vertical structure of the Convective Boundary Layer revealed the four layered structure *viz.* surface layer, sub cloud layer, cloud layer and capping stable layer. These layers could be separated from each other by utilizing the averaged vertical profiles of saturation pressure deficit (P^*, hPa) and mixing parameter (β, dimensionless). The CBL top is marked by the minimum value of P^*. The study revealed that, in general, the extent of surface and sub cloud layer over the north Indian Oceanic regions is up to 1000 hPa and 950 hPa respectively. Also, it is observed that the cloud layer depth varies during the phases IA, IB, II and III. The investigations revealed that the depth of the CBL is up to 650 hPa during all the three phases over the ships.

Key words – Convective boundary layer, Marine boundary layer, Monsoon boundary layer, Sub layers in the CBL, Vertical structure of the CBL, Summer monsoon season.

1. Introduction

The Convective Boundary Layer (CBL) over tropical and subtropical oceans plays a critical role in regulating surface energy and moisture fluxes and controlling the convective transfer of energy and moisture to the free atmosphere. Hence, the knowledge of the structure of the CBL is therefore basic to an understanding of the thermodynamics of the large-scale atmospheric circulations. Significant advances have been made in recent years for the understanding of the physics and to explore its vertical structure. The thermodynamic structure of the CBL over the oceanic regions has been investigated using conserved variable analysis (Betts and Albrecht, 1987; Parasnis and Morwal, 1993a; 1993b; Morwal, 2000; 2002).

The tropical boundary layer differs from the boundary layer at mid and high latitudes. As one moves towards the equator the Coriolis force changes, which in turn changes the dynamics of the tropical boundary layer. Another important difference is the relatively high

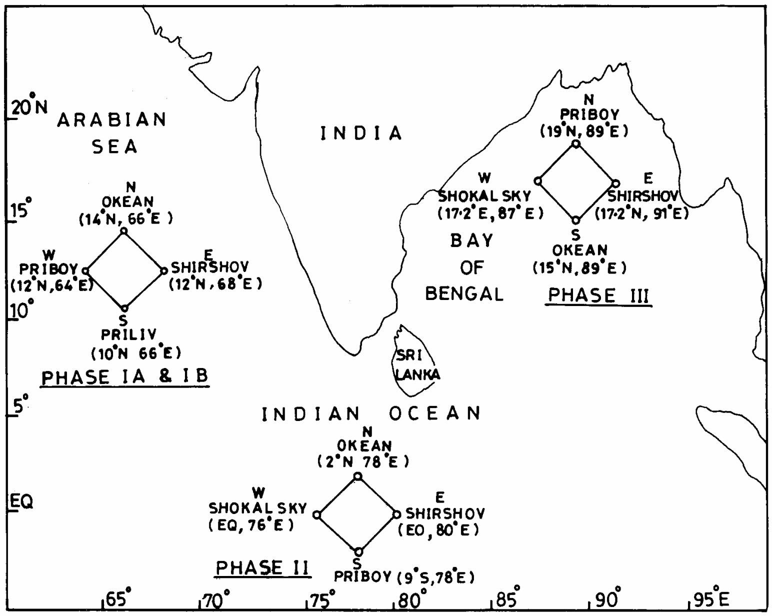


Fig. 1. Location of the ships (denoted by open circle) during the stationary positions in the phases IA, IB, II and III over the north Indian Ocean

moisture content of the tropical boundary layer provided by evaporation of water from the oceans in the tropics (Malkus, 1962). During the undisturbed atmospheric conditions the tropical boundary layer has well defined multilayered structure. The different layers are surface layer, mixed (sub cloud) layer, transition layer, cloud layer and inversion (highly stable) layer. These layers are characterized by different temperature and moisture lapse rates (Malkus, 1956). The structure of the boundary layer observed during the southwest monsoon is different from the tropical boundary layer in many aspects – one of which is its generation and another is the driving force which is responsible for establishment of the monsoon (Holt and Sethuraman, 1986).

In view of the above, it is interesting to study the structure of the CBL during the summer monsoon season, since due to moist convective activity inversion layers are either not present or found at higher levels. In this paper an attempt has been made to use a different approach for delineating the different sub layers of the CBL and to confirm its applicability to the observations collected through MONSOON-77 experiment over the north Indian Oceanic regions during the summer monsoon season. For this purpose concepts of Saturation Point (SP) and mixing parameter (β) have been utilized. The use of the air parcel Saturation Point has proved of great value in interpreting and modeling atmospheric CBL and transport (Betts, 1985). The SP frame work is discussed and used by many workers in their papers (Betts, 1982a; b; 1983; Betts and Albrecht, 1987; Parasnis and Morwal, 1991; Parasnis, 1991; Morwal, 1998).

2. Location of observations and data

MONSOON-77 was conducted over the north Indian Ocean during the summer monsoon season of 1977. The experiment was completed in three phases *viz.* Arabian Sea Phase of Monsoon-77 (Phase IA & IB), Equatorial Indian Ocean phase of Monsoon-77 (Phase II) and Bay of Bengal phase of Monsoon-77 (Phase III). The experiment started on 7 June 1977 with Phase IA in the Arabian Sea and ended with Phase III in the Bay of Bengal on 21 August 1977. In all five erstwhile USSR research vessels *viz*. Shirshov, Okean, Priboy, Priliv and Shokalsky have been used. Out of these five ships only four research vessels which were stationary during the period of observation and formed a polygon were utilized to collect the observations over the above mentioned oceanic regions. Daily four radiosonde ascents were made at 0000, 0600,1200 and 1800 UTC synoptic hours.

In the present paper, in order to delineate the different sub layers in the CBL, aerological observations at an interval of 25-30 hPa from surface up to 400 hPa have been considered. Fig. 1 shows the location of four research vessels (open circle) in the stationary polygons for all the phases. The periods of deployment and the position of stationary observation for the phases IA, IB, II and III were 7 – 20 June 1977 (10° – 14° N, 64° – 68° E), 29 June – 16 July 1977 (10° – 14° N, 64° – 68° E), 25 – 31 July 1977 (2° S – 2° N, 76° – 80° E) and 11 – 18 August 1977 (15° – 19°N, 87° – 91°E) respectively. During the Phase IA the southwest monsoon over the Arabian Sea was in the transient onset conditions whereas during Phase IB, Phase II and Phase III the southwest monsoon has completely spread over the Indian regions. The prevailing synoptic weather conditions during the observational periods in Phase IA, IB, II and III are described elsewhere (Parasnis and Morwal, 1993a; Morwal, 2000 and Morwal, 2002).

3. Method of analysis

In order to differentiate the different sub layers in the vertical structure of the CBL over the oceanic regions a different method is introduced in this paper. The method is based on the Saturation Point (SP) concept. The concept of Saturation Point was introduced by Betts (1982). When an unsaturated air parcel is lifted dry adiabatically to a level where it attains saturation with the available moisture, then that level is known as Saturation Level (SL) and is denoted by p_{SL}. A point on this level, which is uniquely specified by (p_{SL}, θ_{SL}, q_{SL}) is known as saturation point. The saturation point is unchanged during dry/moist adiabatic ascent or descent. A parameter called saturation pressure deficit (P*) can be defined as

$$P^* = p_{SL} - p$$

Where p is the pressure of the air parcel. P* is an indicator of lack of saturation in the layer p to p_{SL}. It is positive in the cloudy regions and negative in the unsaturated regions. High negative values of P* are indicative of more subsaturation or low relative humidity. P* is very useful to delineate the different sub layers in the CBL. The slope of P* is different in different sub layers. Another parameter, β, is defined as

$$\beta = \frac{\partial p_{SL}}{\partial p}$$

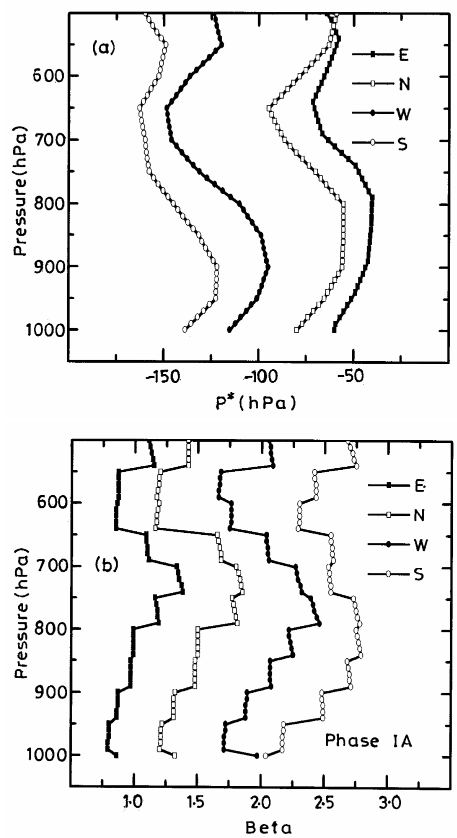
The vertical distribution of p_{SL}(p) and β (p) are unlikely to be the same for all convective regimes (Betts, 1982a). In well mixed stratocumulus layer, the entire cloud and sub cloud layer is thoroughly mixed approximately to a single SP corresponding to β= 0 up to the cloud top inversion (Betts, 1985). In shallow cumulus layer there is some uncoupling between the sub cloud and cloud layers so that the cloud is not thoroughly mixed as the sub cloud layer, this corresponds to a larger value of β (< 1). In transition between scattered cumulus and well mixed stratocumulus layer, there clearly exists the possibility of β in the range 0 to 1. Thus the diagnostic study of boundary layer in terms of their distribution of p_{SL} (p) provides a framework both for classification and assessment of degree of mixing within and between sub layers as well as a powerful framework for a general parameterization of boundary layer structure (Betts, 1985).

In the present study radiosonde observations collected by research vessels in the stationary positions at 6-houry interval have been used. The values of temperature (*T*) and dew point temperature (T_d) which are available at an interval of 25 – 30 hPa are subjected to linear interpolation using 1-2-1 filter in order to get the values at an interval of 10 hPa for each individual ascents. These interpolated values have been used to get the average vertical profiles of *T* and T_d for each ship for different phases. Different thermodynamical parameters such as saturation level pressure (p_{SL}, hPa), mixing parameter (β, dimensionless), saturation pressure deficit (P*, hPa) have been computed from surface up to 400 hPa level at an interval of 10 hPa utilizing averaged vertical profiles of *T* and T_d.

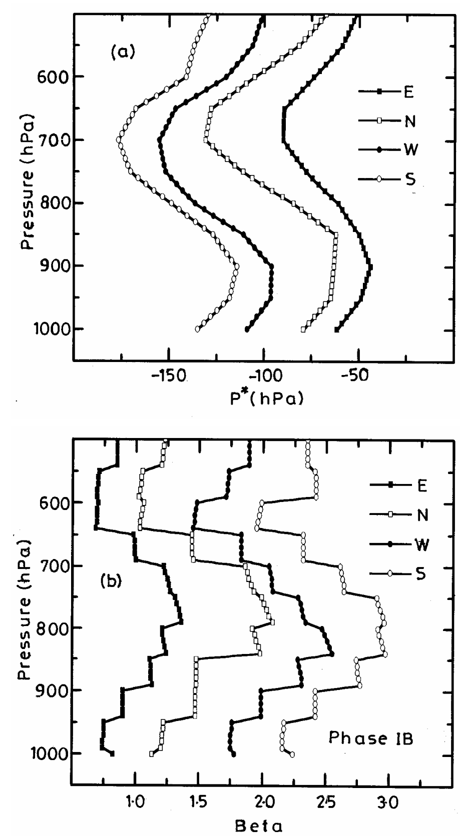
4. Results and discussion

It is observed from the previous investigations (Parasnis and Morwal, 1993a; Morwal, 1998; 2000) that P* profiles show different slopes in different sub layers of the CBL which include surface layer, sub cloud layer, cloud layer and stable layer. Also, average value of β differs in different sub layers (Parasnis, 1991). Therefore, in order to differentiate the various sub layers in the CBL the approach used is described below.

The surface layer is characterized by abrupt change in β values. It is very shallow layer (depth < 10 hPa) just adjacent to the ocean surface. This layer is topped by sub cloud layer which is associated with increasing trend of P* values and nearly constant values of β (slope < 0.2 per 100 hPa). The sub cloud layer is generally well mixed and the *T* and T_d profiles converge in this layer. The next layer is cloud layer which has nearly constant values of P* and continuously increasing trend of β. Maximum values of the P* is the characteristic feature observed in the cloud layer. In this layer the *T* and T_d profiles are nearly parallel to each other. Above cloud layer exists a layer that is more stable as compared to cloud layer. *T* and T_d profiles diverge from each other in this layer. This is termed as capping stable layer or capping inversion layer depending on the stability of the layer. In this layer both P* and β show decreasing trend. The β profiles show a sudden jump at the top of each sub layer which is considered as the delimiter between the different sub layers. The CBL top is associated with minimum value of P* and β shows a sudden drop above the CBL top.



Figs. 2(a&b). Average vertical profiles of (a) Saturation Pressure Deficit P* (shifted by –25 hPa for N, –50 hPa for W and –75 hPa for S) and (b) Mixing parameter β (shifted by 0.5 units for N, 1.0 units for W and 1.5 units for S) during the phase IA over the Arabian Sea



Figs. 3(a&b). Same as Figs. 2(a&b) during the phase IB over the Arabian Sea

The aerological observations considered in the present study are collected over the oceanic regions during southwest monsoon season *i.e.* June – August 1977. In the Arabian Sea Phase (Phase IA and IB) the research vessels forming the polygon were Shirshov (E), Okean (N), Priboy (W) and Priliv (S). Whereas in the Equatorial Indian Ocean phase (Phase II) and Bay of Bengal phase (Phase III) the research vessels were Shirshov (E), Okean (N in Phase II and S in Phase III), Priboy (S in Phase II and N in phase III) and Shokalsky (W). Over the same regions Rao *et al*. (1985) utilized the surface marine meteorological and solar radiation data to describe the space-time variability of surface atmospheric layer characteristics and the ocean surface heat budget components. However, there is no study carried out that utilizes the whole aerological data set available (during the stationary periods) from the MONSOON-77 experiment. With this in view, the above study is undertaken and the results of the investigation over the three regions are discussed in the following subsections.

4.1. *Arabian sea phase (phases IA and IB)*

The number of radiosonde soundings undertaken over the Arabian Sea region during the Phase IA over the four ships *viz*. Shirshov, Okean, Priboy and Priliv are 54, 37, 49 and 52 whereas they are 70, 71, 69 and 69 in case of Phase IB. The vertical profiles of average P* and β for the Phases IA and IB are shown in Figs. 2(a&b) and Figs. 3 (a&b) respectively. Tables 1 and 2 give the details like the number of radiosonde ascents, surface pressure, Lifting Condensation Level (LCL), CBL top, P* at CBL top and average values of β and P* in different sub layers along with top of each layer for different ships in Phases IA and IB respectively.

By following the criteria described above for determining the extent of different sub layers in the CBL it is seen from Figs. 2 (a&b) that the extent of the surface layer is from the ocean surface up to 1000 hPa over the different ships in Phase IA. In this layer average values of β vary from 0.54 to 0.97 and P* is in the range of –55.5 to –65.6 hPa (Table 1). The sub cloud layer extends up to 950 hPa over Priboy (W) and Priliv (S) whereas it is up to 900 hPa over Shirshov (E) and Okean (N). In this layer β is nearly constant and P* is gradually increasing.

TABLE 1

Layerwise average values of Mixing parameter β and Saturation Pressure Deficit P* along with surface pressure, LCL, CBL top and P* at the CBL top during the Phase IA over the Arabian Sea

Parameter	Ship			
	Shirshov (E) (12°N, 68°E)	Okean (N) (14°N, 66°E)	Priboy (W) (12°N, 64°E)	Priliv (S) (10°N, 66°E)
No. of obs.	54	37	49	52
Surface pressure (hPa)	1005.2	1005.8	1005.8	1007.7
LCL (hPa)	945.09	949.75	940.46	940.28
Surface layer				
Top (hPa)	1000.0	1000.0	1000.0	1000.0
Avg. β	0.86	0.82	0.97	0.54
Avg. P* (hPa)	-59.8	-55.5	-65.3	-65.6
Sub cloud layer				
Top (hPa)	900.00	900.00	950.00	950.00
Avg. β	0.83	0.76	0.71	0.67
Avg. P* (hPa)	-49.14	-40.57	-56.53	-54.0
Cloud layer				
Top (hPa)	750.00	750.00	800.00	850.00
Avg. β	1.05	1.09	1.06	1.09
Avg. P* (hPa)	-42.50	-33.51	-50.13	-49.98
Stable layer				
Top (hPa)	650.00	650.00	650.00	650.00
Avg. β	1.23	1.25	1.26	1.16
Avg. P* (hPa)	-65.0	-61.01	-87.11	-78.46
CBL top (hPa)	650	650	650	650
P* at CBL top (hPa)	-71.63	-69.97	-98.49	-87.88

Over the ships Shirshov, Okean, Priboy and Priliv the average values of β and P* in the sub cloud layer are 0.83, 0.76, 0.71, 0.67 and −49.14, −40.4, −56.53, −54.0 respectively. It is noticed that over all the ships β is minimum in the sub cloud layer as compared to that in other layers except over Priliv. The minimum value of β in the sub cloud layer (or mixed layer) indicates that sub cloud layers are more well mixed as compared to other layers in the CBL. The cloud layer, which is above the sub cloud layer, varies in the range 850–750 hPa for the four locations. From Table 1 it is seen that the value of P* is maximum in cloud layer indicating less sub saturation (or more humidity) in this layer in comparison to other layers. The cloud layer is capped by a more stable layer, which extends up to 650 hPa at all the ships. In this layer β shows sharp increasing trend whereas P* decreases sharply. The CBL top is observed at 650 hPa over all the four vertices of the polygon and is associated with minimum value of P*.

These values are comparable to those obtained by Parasnis and Morwal (1993a) over the same region utilizing the limited data set from the present data set. Thus it is evident from average values of β and P* in different layers that β is minimum in sub cloud layer and shows increasing trend through cloud layer up to stable layer whereas the P* is maximum in the cloud layer and minimum in the stable layer. Also, from Table 1 it is observed that the values of β for all the ships in cloud layer (1.05 < β < 1.09) are less than that of the overlying stable layer (1.16 < β < 1.26) indicating less mixing in the stable layer. β indicates the amount of mixing present in the layer which is indirectly related to the stability of the layer. Thus the above study indicates that the influence of the ocean surface is more visible up to cloud layer (more mixed) as compared to layers above (mixing is less or stability in the layer is more).

TABLE 2

Layerwise average values of Mixing parameter β and Saturation Pressure Deficit P* along with surface pressure, LCL, CBL top during the Phase IB over the Arabian Sea

Parameter	Ship			
	Shirshov (E) (12°N, 68°E)	Okean (N) (14°N, 66°E)	Priboy (W) (12°N, 64°E)	Priliv (S) (10°N, 66°E)
No. of obs.	70	71	69	69
Surface Pressure (hPa)	1005.7	1005.7	1006.1	1008.0
LCL (hPa)	943.15	949.46	945.88	946.07
Surface layer				
Top (hPa)	1000.0	1000.0	1000.0	1000.0
Avg. β	0.82	0.63	0.78	0.74
Avg. P* (hPa)	-62.0	-55.2	-59.2	-60.9
Sub cloud layer				
Top (hPa)	950.00	950.00	950.00	950.00
Avg. β	0.75	0.71	0.75	0.66
Avg. P* (hPa)	-53.8	-45.44	-51.36	-49.73
Cloud layer				
Top (hPa)	800.00	800.00	850.00	850.00
Avg. β	1.08	1.13	1.14	1.09
Avg. P* (hPa)	-49.97	-42.36	-50.6	-43.91
Stable layer				
Top (hPa)	700.00	700.00	700.00	700.00
Avg. β	1.29	1.46	1.30	1.33
Avg. P* (hPa)	-78.23	-87.17	-92.15	-83.96
CBL top (hPa)	700	700	700	700
P* at CBL top (hPa)	-89.95	-105.91	-105.22	-101.82

From Figs. 3 (a&b), which depicts vertical profiles of average P* and β for Phase IB over all the ships, it is observed that the surface layer extends from sea surface up to 1000 hPa with β and P* varying form 0.63 to 0.82 and –55.2 to –62.0 hPa respectively. The sub cloud layer, in general, extends up to 950 hPa and is associated with minimum values of β (varies from 0.68 to 0.75) as compared to other layers. In the cloud layer P* varies from –45.4 to –53.8 hPa over the four locations in Phase IB. The extent of the cloud layer is up to 850 hPa over Priboy and Priliv and up to 800 hPa over Shirshov and Okean. The cloud layer is deeper at Shirshov and Okean as compared to that over Priboy and Priliv which is the effect of prevailing weather conditions and synoptic scale disturbances as stated by Parasnis and Morwal (1993a). Here it is noticed that in the cloud layer P* has maximum values (*i.e.* maximum relative humidity) and β has high values as compared to sub cloud layer for all the ships. The stable layer is up to 700 hPa over all the ships and is associated with average values of β and P* in the range 1.29 to 1.46 and –78.23 to –92.15 hPa respectively. The top of the stable layer is considered as the CBL top which is observed at 700 hPa and is associated with the minimum value of P* as seen from Table 2. The CBL top in Phase IB is lower by 50 hPa than that of Phase IA. It is clearly evident that in both the Phases *i.e.* IA and IB β and P* show the similar tendencies in the different layers in the CBL. Thus vertical profiles of β and P* can be used to delineate the different sub layers in the CBL.

Phase IA is associated with onset of southwest monsoon and the period in Phase IB coincides with the active monsoon conditions. A study carried out by Parasnis and Morwal (1993a) to investigate the thermodynamical characteristics of the CBL over the same region utilizing the part of the data showed that during the onset period (Phase IA) the frequency of occurrence of q-reversals is negligible as compared to active phase of monsoon (Phase IB). The present study conducted using the all available data corroborates the results obtained by

TABLE 3

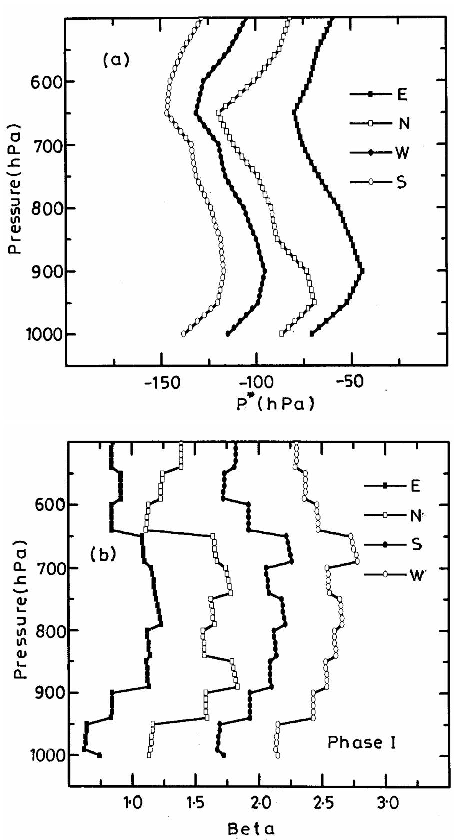
Layerwise average values of Mixing parameter β and Saturation Pressure Deficit P* along with surface pressure, LCL, CBL top during the Phase II over the Equatorial Indian Ocean

Parameters	Ship: Shirshov (E) (0°N, 80°E)	Okean (N) (2°N, 78°E)		Shokalsky (W) (0°N, 76°E)	Priboy (S) (2°S, 78°E)
No. of obs.	24	24		21	24
Surface Pressure (hPa)	1007.5	1008.9		1008.2	1008.6
LCL (hPa)	934.65	943.77		940.85	942.21
Surface layer					
Top (hPa)	1000.0	-		1000.00	1000.00
Avg. β	0.74	-		0.72	0.65
Avg. P* (hPa)	-71.9	-		-66.2	-64.9
Sub cloud layer					
		(1)	(2)		
Top (hPa)	950.00	950.00	800.00	950.00	950.00
Avg. β	0.63	0.65	1.07	0.68	0.64
Avg. P* (hPa)	-59.74	-53.0	-66.0	-55.45	-52.52
Cloud layer					
		(1)	(2)		
Top (hPa)	800.00	900.00	750.00	800.00	700.00
Avg. β	1.03	1.08	1.14	1.05	1.05
Avg. P* (hPa)	-49.91	-46.9	-71.5	-49.83	-49.05
Stable layer					
		(1)	(2)		
Top (hPa)	650.00	850.00	650.00	650.00	650.00
Avg. β	1.15	1.31	1.21	1.17	1.25
Avg. P* (hPa)	-71.3	-58.0	-87.0	-69.3	-66.88
CBL top (hPa)	650	650		650	650
P* at CBL top (hPa)	-79.88	-94.77		-81.59	-71.74

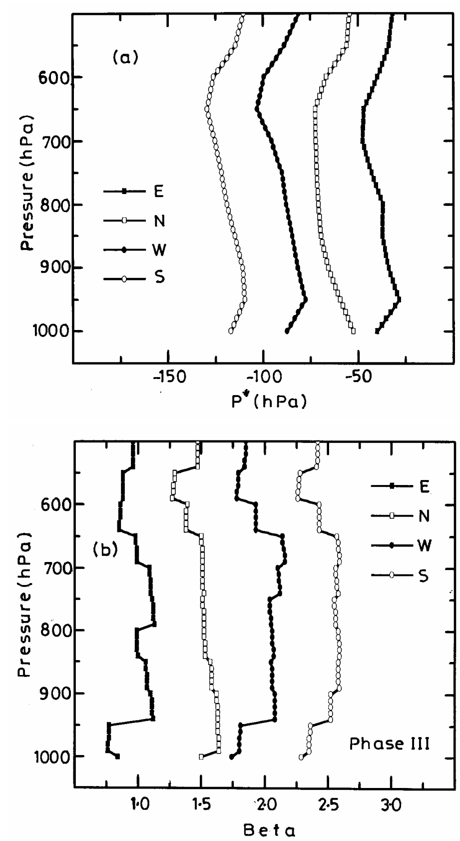
Parasnis and Morwal (1993a). By comparing the values of β over the four ships during the Phase IA and IB it is evident that the stable layers during Phase IB are associated with higher stability.

4.2. *Equatorial Indian Ocean phase (Phase II)*

The stationary period 25-31 July, 1977 when the aerological observations were collected over the four ships (Shirshov, Okean, Priboy and Shokalsky), belongs to Equatorial Indian Ocean region (2° S - 2° N, 76° - 80° E). The total number of radiosonde observations undertaken in Phase II are 93. The ship wise distribution is shown in Table 3. The vertical profiles of average P* and β for all the ships are shown in Figs. 4(a&b). Table 3 gives the layerwise distribution of average values of β and P* for all the ships. Also, information like surface pressure, LCL height, CBL top is included in this Table. Over all the ships the mean surface layer height is up to 1000 hPa and sub cloud layer is up to 950 hPa which is represented by a minimum average values of β. The depth of cloud layer lies between 950-800 and 950-700 hPa over the E and W and S locations respectively and are found to be associated with maximum of P* values. Whereas over the N location the double cloud layers are observed between 950-900 hPa and 800-750 hPa. Thus the cloud layers are thicker for the ship located in the south of equator as compared to that over north or equator. For the ships located at the equator the cloud thickness is same. This supports the findings of Morwal (2000). The stable layer overlying the cloud layer extends up to 650 hPa which also represents the CBL top. In this layer the average values of P* is



Figs. 4(a&b). Same as Figs. 2(a&b) during the phase II over the Equatorial Indian Ocean



Figs. 5(a&b). Same as Figs. 2(a&b) during the phase III over the Bay of Bengal

minimum and β is maximum. From Table 3 it is noticed that the values of P* for Priboy, which is located south of the Equator, is more in all the layers as compared to that over other ships indicating more saturation in the CBL. Also, the layerwise averages of P* at the two ships (Shirshov and Shokalsky) located at the Equator are more or less similar implying that CBL has more or less similar CBL characteristics at the two locations separated by 4° longitudes. CBL is less saturated at the location north of Equator as seen from P* values in different layers.

4.3. *Bay of Bengal phase (phase III)*

The radiosonde ascents were taken during the period 11–18 August 1977, when the four research vessels forming polygon were stationary, in the northern Bay of Bengal region (15° - 19° N, 87° - 91° E). Total 115 soundings have been considered for the present study. The vertical profiles of average values of P* and β at the four locations are shown in Figs. 5(a&b) respectively. Layerwise average values of β and P* and other parameters like surface pressure, LCL, CBL top for the four ships are given in Table 4. From Fig. 5 it is clearly evident that in this phase the extent of the surface layer and sub cloud layer is up to 1000 hPa and 950 hPa respectively. The P* shows increasing trend in the sub cloud layer and the average value varies in the range –29.9 to –42.7 hPa. In the surface layer average values of β have no specific trend however they are found to be minimum in the sub cloud layer except for the ship Priboy (Table 4). The cloud layer is represented by nearly constant values of P* and the average value of β is same over all the ships (1.06). In general, the cloud layer extends up to 750 hPa but at Shirshov it is shallow and is limited to 800 hPa. In a similar way the stable layer is associated with sharp decreasing trend of P* with the lowest value at the CBL top which is at 650 hPa over all the ships except over Shirshov. The stable layer is represented by the highest average values of β and minimum values of P* averages. The results obtained over the Bay of Bengal region are in support of the investigations carried out by Morwal (2002).

Rao *et al.* (1985) observed that the surface layer of Bay of Bengal is more saturated than that of Arabian Sea during MONSOON-77 experiment, which is in support of

TABLE 4

Layerwise average values of Mixing parameter β and Saturation Pressure Deficit P* along with surface pressure, LCL, CBL top during the Phase III over the Bay of Bengal

	Ship			
Parameter	Shirshov (E) (17°N, 91°E)	Priboy (N) (19°N, 89°E)	Shokalsky (W) (17°N, 87°E)	Okean (S) (15°N, 89°E)
No. of obs.	24	31	28	32
Surface Pressure (hPa)	1004.8	1004.2	1004.8	1007.0
LCL (hPa)	967.64	971.89	966.03	963.52
	Surface layer			
Top (hPa)	1000.0	1000.0	1000.0	1000.0
Avg. β	1.6	-0.14	0.74	0.79
Avg. P* (hPa)	-38.6	-29.9	-38.2	-42.7
	Sub cloud layer			
Top (hPa)	950.00	950.00	950.00	950.00
Avg. β	0.77	1.14	0.80	0.85
Avg. P* (hPa)	-32.99	-31.74	-31.64	-37.59
	Cloud layer			
Top (hPa)	800.00	750.00	750.00	750.00
Avg. β	1.06	1.06	1.06	1.06
Avg. P* (hPa)	-34.9	-43.3	-34.9	-40.4
	Stable layer			
Top (hPa)	700.00	650.00	650.00	650.00
Avg. β	1.11	1.01	1.13	1.08
Avg. P* (hPa)	-43.2	-47.3	-46.9	-51.0
CBL top (hPa)	700	650	650	650
P* at CBL top (hPa)	-47.7	-47.57	-53.16	-54.47

less subsaturation (or high relative humidity) observed over the Bay of Bengal region as compared to those over Arabian Sea and Equatorial Indian Ocean regions.

5. Summary of the results

The investigations have been carried out to explore the utilization of the method to delineate the different sub layers in the Convective Boundary Layer during the summer monsoon season over the Indian Oceanic regions. For this purpose the complete data set consisting of aerological observations collected through MONSOON-77 experiment over the Arabian Sea, Equatorial Indian Ocean and Bay of Bengal regions during southwest monsoon (June–August 1977) of 1977 have been considered. The application of the method confirms its usefulness in determining the different sub layers in the CBL and the results of the study are summarized as follows.

The vertical structure of the CBL includes four sub layers *i.e.* surface layer, sub cloud or mixed layer, cloud layer and the overlying stable layer. The vertical profiles of P* and β have different slopes in different sub layers and are separated by a sudden jump in vertical profiles of β.

The extent of the surface layer, characterized by abrupt slopes of P* and β, is found to be from the ocean surface up to 1000 hPa over all the ships and during all the three phases *i.e.* Phase IA and IB, Phase II and Phase III.

The sub cloud layer above the surface layer is associated with increasing trend of P* and minimum values of β (< 1.0). The sub cloud layer, in general, extends up to 950 hPa which is in agreement with the previous findings over the Arabian Sea region (Parasnis and Morwal, 1993), Equatorial Indian Oceanic regions

(Morwal, 2000) and Bay of Bengal (Morwal, 2002; Bhat *et al.*, 2000).

The cloud layer which is above the sub cloud layer and below the capping stable layer has maximum values of P* and values of β continuously increasing. In general β is nearly equal to 1.0 and P* is nearly constant in the cloud layer. The depth of the cloud during the Phase IA and IB, Phase II and Phase III lies between 100-150 hPa, 50-250 hPa and 150-200 hPa respectively. The cloud layer thickness is more over the southern equatorial Indian oceanic region as compared to that over northern and equatorial regions and also Arabian Sea and Bay of Bengal regions.

The capping stable layer overlying the cloud layer is specified by the decreasing values of P* and increasing trend of β. The CBL top is associated with the minimum value of P*. The average profiles of P* and β showed that the CBL over the north Indian Oceanic regions extends up to 650 hPa for all the phases during the summer monsoon season.

Acknowledgements

The author is thankful to the Director, Indian Institute of Tropical Meteorology (IITM), Pune, for the facilities provided for carrying out this work. Author would like to thank Dr. P.C.S. Devara, Head (PM&A Division) and Deputy Director, for encouragement and keen interest during the course of this study. Author is grateful to Dr. P. Ernest Raj for fruitful discussion and suggestions during the preparation of the manuscript and also for careful examination of the manuscript. The ship data used in the above study has been obtained from Indian Meteorological Department. The author gratefully acknowledges International MONEX Management Centre (IMMC), New Delhi and ADGM (R) Office, Pune for the data source. The author is very thankful to the anonymous referee for useful suggestions, which were very helpful in the modification of the revised manuscript.

References

Bhat, G. S., Ameenulla, S., Venkataramana, M. and Sengupta, K., 2000, "Atmospheric boundary layer characteristics during BOBMEX-Pilot experiment", *Proc. Indian Acad. Sci. (Earth Planet. Sci.)*, **109**, 229-237.

Betts, A. K., 1982a, "Saturation point analysis of moist convective overturning", *J. Atmos. Sci.,* **39**, 1484-1505.

Betts, A. K., 1982b, "Cloud thermodynamic models in saturation point coordinates", *J. Atmos. Sci.,* **39**, 2182-2191.

Betts, A. K., 1983, "Thermodynamics of mixed stratocumulus layers : Saturation point budgets", *J. Atmos. Sci.,* **40**, 2655-2670.

Betts, A. K., 1985, "Mixing line analysis of clouds and cloudy boundary layers", *J. Atmos. Sci.,* **42**, 2751-2763.

Betts, A. K. and Albrecht, B. A., 1987, "Conserved variable analysis of the convective boundary layer thermodynamic structure over the tropical oceans", *J. Atmos. Sci.,* **44**, 83-99.

Holt, T. and Sethuraman, S., 1986, "Observations of the mean and turbulence structure of the marine boundary layer over the Bay of Bengal during MONEX-79", *Mon. Wea. Rev.*, **114**, 2176-2190.

Malkus, J. S., 1956, "On the maintenance of trade winds", *Tellus*, **8**, 335-350.

Malkus, J. S., 1962, "Large-scale interaction, Chapter 4 in The Sea. Vol. I : Ideas and observations on Progress in study of the sea", M.N. Hill, I, Ed. Willey-Interscience, 288-294.

Morwal, S. B., 1998, "Nature and some evolutionary aspects of the monsoon boundary layer", Ph.D. thesis, p213.

Morwal, S. B., 2000, "Convective boundary layer structure over the Equatorial Indian oceanic region", *Mausam*, **51**, 169-176.

Morwal, S. B., 2002, "Some aspects of the Convective Boundary Layer over the Bay of Bengal", *Atmosfera,* **15**, 39-54.

Parasnis, S. S., 1991, "Convective mixing in the monsoon boundary layer", *Bound.Layer Meteorol.*, **56**, 395-400.

Parasnis, S. S. and Morwal, S. B., 1991, "Mixing processes in the atmospheric boundary layer during summer monsoon", *Acta Meteorologica Sinica*, **5**, 259-263.

Parasnis, S. S. and Morwal, S. B., 1993a, "Thermodynamic structure of the marine boundary layer over the Arabian Sea as revealed by the MONSOON-77 data", *Bound.Layer Meteorol.*, **63**, 365-380.

Parasnis, S. S. and Morwal, S. B., 1993b, "Radiatively driven subsidence over the Eastern Arabian sea with MONSOON-77 data", *Ind.J.Radio and Space Physics*, **22**, 235-238.

Rao, R. R., Raman, K.V.S., Rao, D. S. and Joseph, M. X., 1985, "Surface Heat Budget Estimation at Selected Areas of North Indian Ocean during Monsoon-77", *Mausam*, **36**, 21-32.