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Planetary boundary layer structure in the monsoon trough region

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सार — मॉन्टब्लेक्स 1989 के प्रायोगिक आंकड़ों के आधार पर मानसून द्रोणी के क्षेत्र में भूमंडलीय परिसीमा परत (पी बी एल) का अध्ययन किया गया है। स्थल क्षेत्र पर भूमंडलीय परिसीमा की संरचना व्यापक क्षेत्रीय और सामयिक परिवर्तनों को दर्शाती है। तीन प्रकार की भूमंडलीय परिसीमा परतों का पता चला है—उथली संवहनी, मानसूनी तथा शुष्क संवहनी परिसीमा परतें। विभिन्न प्रकार की भूमंडलीय परिसीमा परतों के अभिलक्षणों की पहचान की गई है और उन्हें इस शोध-पत्र में प्रस्तुत किया गया है। मानसून द्रोणी के पूर्वी, मध्य तथा पश्चिमी क्षेत्रों में पाई गई भूमंडलीय परिसीमा परतों के विश्लेषण की सहायता से मानसून की सक्रिय, क्षीण तथा समाप्त होने की परिस्थितियों के दौरान भारत के गांगेय क्षेत्र के मैदानों में भूमंडलीय परिसीमा परत के स्थानिक अनुप्रस्थ परिच्छेद विकसित करने का प्रयास किया गया है।

ABSTRACT. A study of Planetary Boundary Layer (PBL) in the monsoon trough region has been carried out based on MONTBLEX 1989 pilot experiment data. PBL structure over land shows wide spatial and temporal variations. Three types of PBL—shallow convective, monsoon and dry convective boundary layers have been observed. Characteristic features associated with different types of PBL have been identified and presented in the paper. With the help of observed PBL structure over eastern, central and western sectors of the monsoon trough, attempt has been made to develop space cross-sections of PBL over Indo-Gangetic plains during active, weak and break monsoon conditions.

Key words — PBL, Monsoon trough, Lapse rate, Mixed layer, Inversion, Monsoon.

1. Introduction

The Planetary Boundary Layer (PBL) is that region of the atmosphere where the influence of the ground can be felt through turbulence exchange of momentum, heat and moisture. The PBL occupies an important place in tropics due to the fact that large amount of water vapour contained in this layer over tropical oceans acts as a major source for convective and synoptic scale weather activities. Observations have shown that during undisturbed conditions, tropical boundary layer is characterized by well defined vertical layering (Riehl *et al.* 1951, Malkus 1956, Augustein *et al.* 1974), consisting of surface layer, mixed layer, transient layer, cloud layer and inversion layer. First attempt to study monsoon boundary layer over oceanic region was made during the International Indian Ocean Experiment (IIOE) in 1963-65. It was followed by Indo-Soviet Monsoon Experiment (ISMEX) in 1973 and 1977. It was found that monsoon boundary layer over the ocean was characterized by much stronger lapse rates of humidity (Pant 1978) and an increase of wind with height in the sub-cloud layer (Long 1980). ISMEX data revealed practically no inversion along equator. Inversions were observed along 10°N (Ramanathan 1978 and 1982) where inversion base appears at higher altitudes and inversion strength (temperature increase in the inversion layer) becomes weaker from 50°E to 70°E. The existence of the jet and associated thermal structure and significant advective acceleration in the lower levels of the monsoon boundary layer over the Arabian Sea are characterized by markedly different features from that of the trade wind boundary layer (Holt and Sethuraman 1985). A jet or wind maximum in the upper layers of the boundary layer over the Bay of Bengal is also observed during break monsoon conditions whereas wind profiles obtained during active monsoon periods do not show the wind maximum and the thermal structure during the break monsoon period shows near neutral to slightly unstable stratification over the Bay of Bengal as opposed to slightly stable during active monsoon periods (Holt and Sethuraman 1986). Height of the boundary layer over the Bay of Bengal was observed to be about 400-500 m in contrast to about 800-1500 m reported for the Arabian Sea.

2. Monsoon Trough Boundary Layer Experiment (MONTBLEX)

Due to lack of PBL observations, very little is known about its structure over the land during monsoon season. With a view to fill this void, MONTBLEX was conducted during the 1990 summer monsoon season (Goel and Srivastava 1989). Monsoon trough is one of the important synoptic features of the Indian summer monsoon controlling day-to-day variations of rainfall intensity and distribution over the Indo-Gangetic plains. Monsoon trough extends southeastwards from the seasonal low over the Pakistan and its neighbourhood to the Gangetic West Bengal (Fig. 1). Climatologically average position of the monsoon trough at sea level passes through Ganganagar,

* Air Force Station, Pune.

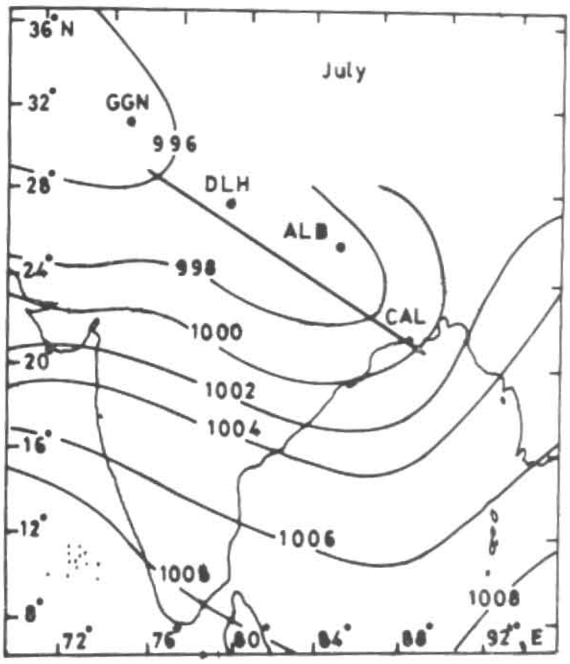


Fig. 1. The monsoon trough over India

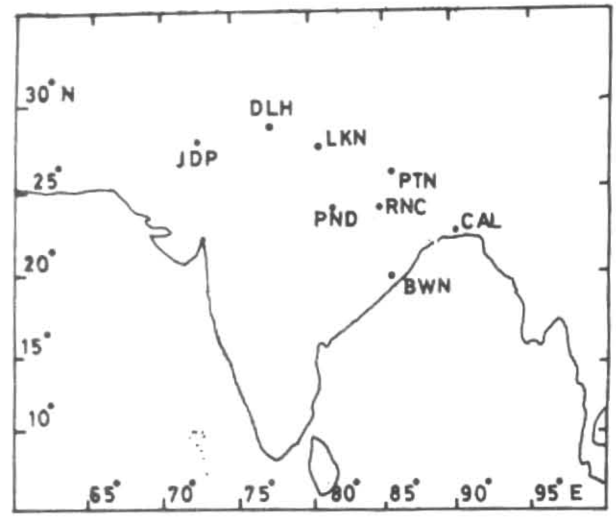


Fig. 2. Location of radiosonde stations

Allahabad and Calcutta (Rao 1976) with westerly to southwesterly winds to the south and easterlies to the north. The trough is seen in the upper air also up to 6.0 km slopping southwards with height. The temperature to the north of the monsoon trough from surface to 500 hPa is observed to be 1-2°C higher than to the south (Srinivasan *et al.* 1971). It is attributed to cool westerly winds in the south (of southern hemisphere and Arabian Sea origin) as compared to easterly winds. MONTBLEX pilot experiment provided useful data set over eastern part of the monsoon trough. Radiosonde/slow rising balloon observations were taken four times a day (0530, 1045, 1730 and 2230 IST) from 2 to 7 July 1989 at Calcutta, Bhubaneswar, Ranchi and Patna. Radiosonde data of Delhi, Lucknow, Pendra and Jodhpur has also been included in the study to have coverage over entire monsoon trough region. Location of these stations are shown in Fig. 2. Synoptic charts and satellite pictures have been analysed for the appreciation of synoptic conditions. Weather observations of these stations have also been made use of in the study. With the help of the above data attempt has been made to study boundary layer in the monsoon trough region. The year 1989 was a good monsoon year for India. Southwest monsoon set in over Kerala on 3 June. The Arabian Sea branch of monsoon current advanced steadily northwards up to south Gujarat by 11 June. The Bay branch of the monsoon advanced over Assam and adjacent States on 6 June. The second phase of the advancement over the northern plains commenced on 13 June and it covered the northern parts of Peninsular India and northern plains up to eastern part of Uttar Pradesh by 23 June. The final phase of advance commenced on 29 June and it covered remaining parts of country by 2 July. During first week of July 1989, there was little monsoon activity over Uttar Pradesh, Rajasthan, Punjab, Haryana and Jammu & Kashmir. Monsoon activity was normal over the West Bengal and below normal over Bihar plains and Orissa during week ending 5 July. During the first week, no major synoptic systems developed over the Bay and monsoon trough at 0.9 km was not well defined. Synoptically weak monsoon conditions prevailed during the week.

3. Classification of the monsoon trough PBL

Profiles of air temperature, dew point, specific humidity, virtual potential temperature and equivalent potential temperature were constructed from the surface to a height of 3 km. Characteristic discontinuities were analysed in the vertical gradients of these elements in the individual profiles. Radiosonde observations reported in 50 hPa interval together with significant level informations are utilized in this study. As the transition layer in the trade wind boundary layer is found to be of about 200 m, presence or absence of the transition layer in the monsoon boundary layer could not be established. Similarly, inversion of smaller thickness, specially on top of the cloud layer could not be resolved. Inspite of these limitations, analysis of 200 radiosonde observations revealed useful information about the PBL over land. Based on the discontinuities and in accordance with the classification used in the literature, following three different types of PBL have been identified :

(*i*) Shallow convective PBL,
(*ii*) Monsoon PBL,
(*iii*) Dry convective PBL.

TABLE 1

Characteristics of different sub-layers of the planetary boundary layer in the monsoon trough region

Type	Mixed layer					Cloud layer				Stable/isothermal layer		
	Height (m)		Lapse rate per 100 m			Depth (m)	Lapse rate per 100 m			Height of base (m)	Lapse rate per 100 m	
	Top	LCL	T	q	θ_v	—	T	q	θ_v	—	q	θ_v
Shallow convective	450	450	0.90	0.20	0.10	900	0.50	0.40	0.40	1450	1.0	0.90
Monsoon	400 to 500	100 to 300	0.65 to 0.75	0.12	0.10 to 0.20	2000 to 3000	0.40 to 0.50	0.30	0.44	2500 to 3500	0.40	0.70 to 0.90
Dry convective	2000 to 3000	1500 to 3000	0.98	0.20	0.046	**	**	**	**	2000 to 3000	0.50	0.45

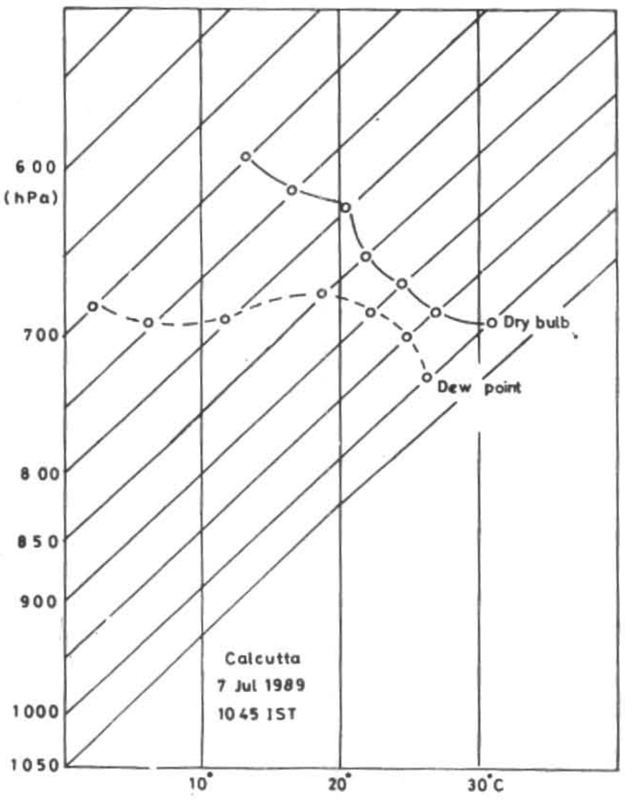


Fig. 3. Tephigram representing shallow convective boundary layer

3.1. *Shallow convective PBL*

Boundary layer of this type exhibits layer structure comprising mixed layer, cloud layer topped by isothermal/stable layer. A tephigram representing the shallow convective boundary layer is shown in Fig. 3. Salient features of individual layers are given in Table 1. Vertical profiles of virtual potential temperature, equivalent potential temperature, wind speed and specific humidity are presented in Fig. 4.

(*i*) *Mixed layer*—This layer is characterized by nearly constant or slight increase of virtual potential temperature (0.1°C/100 m) with height. The lapse rate of temperature is close to dry adiabatic (−0.9°C/100 m) and specific humidity shows slight decrease in these layers. The depth of mixed layer is about 450 m. Lifting Condensation Level (LCL) either coincides with the top of mixed layer or lies within upper 100 m.

(*ii*) *Cloud layer*—It extends from the top of mixed layer to the base of isothermal/stable layer. The lapse rate of temperature in this layer is about 0.5°C/100 m. Specific humidity shows sharper decrease with height as compared to mixed layer [0.3-0.4 (gm/kg)/100 m]. Virtual potential temperature lapse rate is 0.4°C/100 m. The depth of the cloud layer is generally between 700 & 1000 m.

(*iii*) *Isothermal/stable layer*—Stable layer above cloud layer experience sharp decrease in specific humidity at the rate of 1 (gm/kg)/100 m. Lapse rate of virtual potential temperature in the layer increases to about 0.9°C/100 m.

3.2. *Monsoon boundary layer*

Monsoon airmass is characterized by temperature lapse rate slightly more than saturated adiabatic lapse rate with high humidity content. In the presence of high moisture content, an ascent of 50 hPa in the lower levels is able to provide condensation. Monsoon boundary layer is observed to be quite different in many respects as compared to other type of boundary layers. One distinguishing factor is that discontinuity in the vertical gradient of meteorological parameters is not so well marked as in the other boundary layers (Fig. 5). Many a times it becomes difficult to identify layer structure in

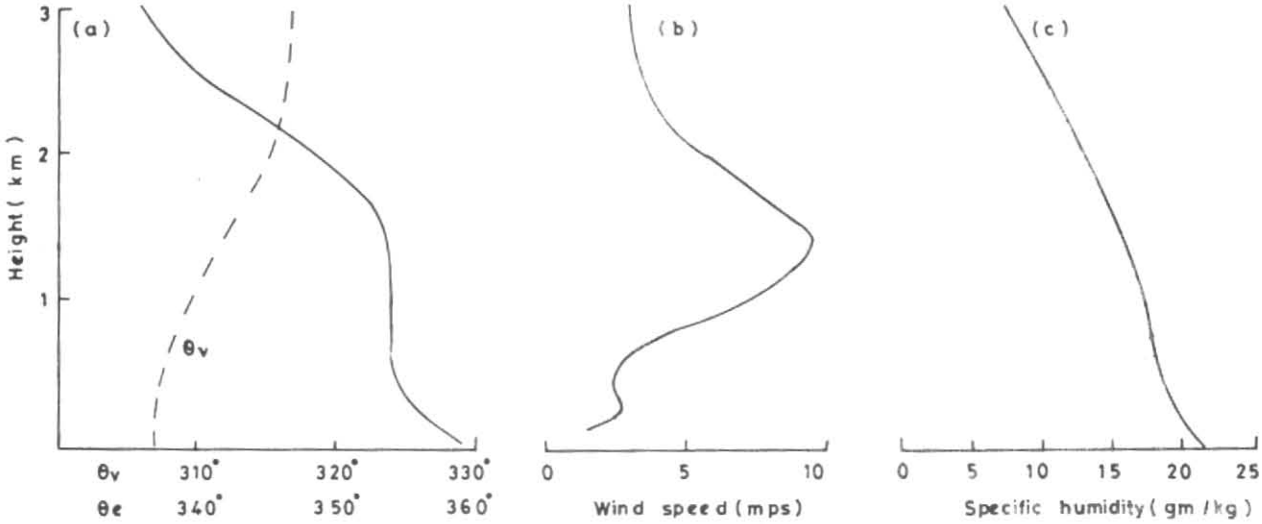


Fig. 4. Thermodynamic profiles associated with shallow convective boundary layer : (a) virtual potential temperature and equivalent potential temperature, (b) wind speed, and (c) specific humidity

monsoon boundary layer. However, on the basis of variations in the vertical gradients it is possible to identify following sub-layers :

(i) Mixed layer—The mixed layer is characterized by nearly constant or slight increase of virtual temperature (< 0.1°C/100 m) with height. The lapse rate of temperature is between dry adiabatic and saturated adiabatic lapse rate (0.7°C/100 m) and specific humidity is nearly constant in the layer.

(ii) Cloud layer—It is deep layer of 2000-3000 m thickness extending from the top of mixed layer to the base of inversion layer. The temperature lapse rate is close to saturated adiabatic lapse rate. The lapse rate of virtual temperature increase from less than 0.1°C/100 m observed in the mixed layer to about 0.44°C/100 m in this layer. Specific humidity shows gradual decrease with height.

(iii) Inversion/isothermal layer—The base of inversion layer varies between 2500 & 3500 m depending upon the thickness of cloud layer. The lapse rate of virtual temperature increases to 0.7-0.9°C/100 m.

Unlike in shallow convective PBL, where sharp decrease in humidity takes place in the layer, gradual decrease of humidity is observed in the case of monsoon PBL. Under favourable synoptic conditions, clouds extend to greater heights and on such occasions it is difficult to differentiate between mixed layer, cloud layer and stable layer as uniform lapse rate prevails from surface to upper troposphere. Most of the PBL structures given in the literature are as observed in the undisturbed conditions. Under disturbed conditions, interactions between mixed layer, cloud layer and the environment become quite complex. Updrafts in the clouds, subsidence in the cloud free areas, drying of the mixed layer during the formation of clouds and impact of precipitation on the sub-cloud layer are some of the interesting phenomena which need to be investigated further in monsoon boundary layer.

3.3. *Dry convective PBL*

Dry convective boundary layer is made up of deep mixed layer with no cloud layer. Mixed layer is topped either by an isothermal or a stable layer. The surface layer associated with this type of boundary layer exhibits super adiabatic lapse rate and sharp decrease in specific humidity. Mixed layer is characterized by nearly constant distribution of virtual potential temperature with height. The lapse rate of temperature is close to dry adiabatic rate and specific humidity lapse rate is 0.2 (gm/km)/100 m. Typical tephigram representing dry convective boundary layer is shown in Fig. 6. The top of boundary layer is about 2 km and rises up to 3 km in intense cases. Sharp decrease of specific humidity is observed in the stable layer [0.5 (gm/kg)/100 m]. The lapse rate of virtual potential temperature is about 0.45°C/100 m. Lifting Condensation Level (LCL) is very high with height ranging between 1.5 & 2.0 km. Fig. 7 depicts vertical profiles of virtual potential temperature, equivalent potential temperature and specific humidity for dry convective PBL.

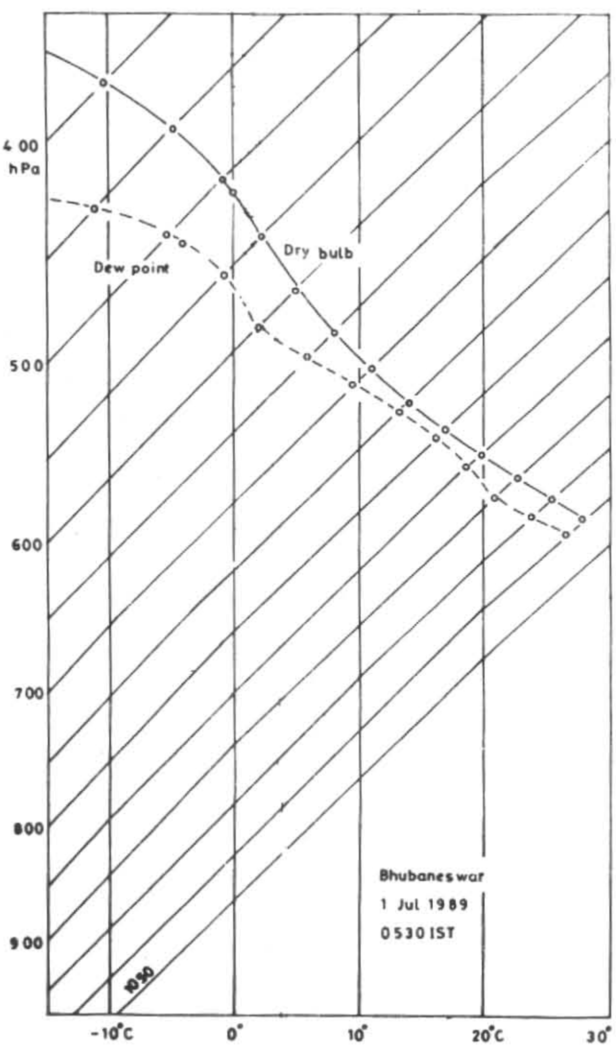


Fig. 5. Tephigram representing monsoon boundary layer

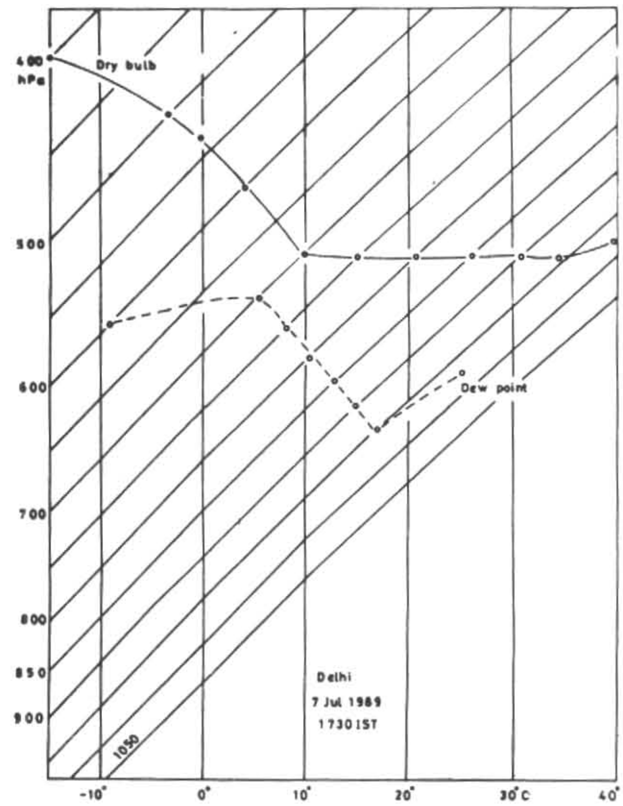


Fig. 6. Tephigram representing dry convective boundary layer

4. PBL characteristics over the monsoon trough region

In order to ascertain PBL characteristics in the monsoon trough region, structure of PBL at three different locations *viz.,* Calcutta, Patna and Delhi was studied in detail. Calcutta represents the maritime conditions, Patna represents an inland station over the eastern part of the monsoon trough and Delhi represents inland station over the western part of the monsoon trough.

4.1. *Calcutta*

Calcutta is an ideal station for the study of boundary layer structure at a coastal region and for comparison with marine boundary layer observed over the Bay of Bengal. Characteristic features of PBL in terms of mixed layer/inversion height, wind direction, low level jet/wind maximum, if any, nature of static and convective stability, height of LCL etc were analysed in respect of four soundings (0530, 1045, 1730 and 2230 IST) each day from 1 to 7 July 1989. It brings out the importance of wind direction in determining the type of PBL at Calcutta. It is observed that low level wind maximum occurs, whenever wind was from south to southwesterly direction at Calcutta. During the period of study, magnitude of wind maximum varied from $7 ms^{-1}$ to $15 ms^{-1}$ and its level of occurrence varied from 150 m to 900 m. In several occasions during the period of study, the wind maximum was found at 600 m. Low level jet is a characteristic feature of marine boundary layer over the Bay of Bengal and Arabian Sea during the monsoon season. Over the Bay of Bengal, level of maximum wind is reported to be at 500 m (Holt and Sethuraman 1986). During the period (2-5 July 1989) when the wind is blowing from southwesterly to westerly direction, no wind maximum was observed and winds in general were found to be weaker. Another interesting feature observed is the marked diurnal variability in the stability characteristics of the mixed layer with the land type of PBL at Calcutta. As this period is characterized by a weak monsoon over the Gangetic West Bengal, the analysis showed that the PBL at Calcutta is of land origin associated with weaker winds, absence of low level jet and marked diurnal variability in the mixed layer characteristics. On the other hand, the presence of marine boundary layer was seen on 1

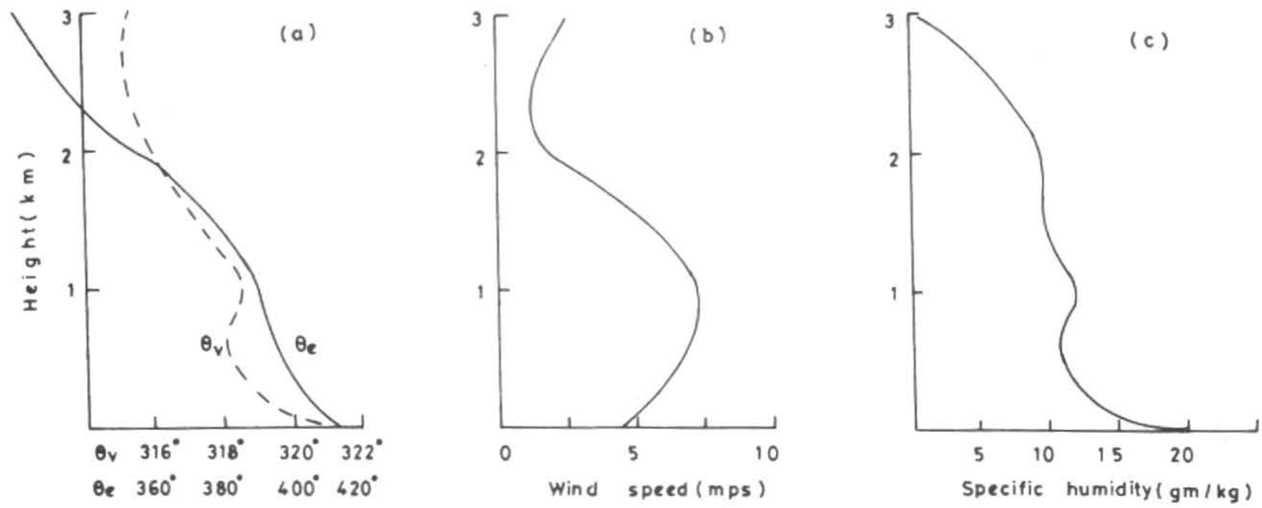


Fig. 7. Same as Fig. 4 but for dry convective boundary layer

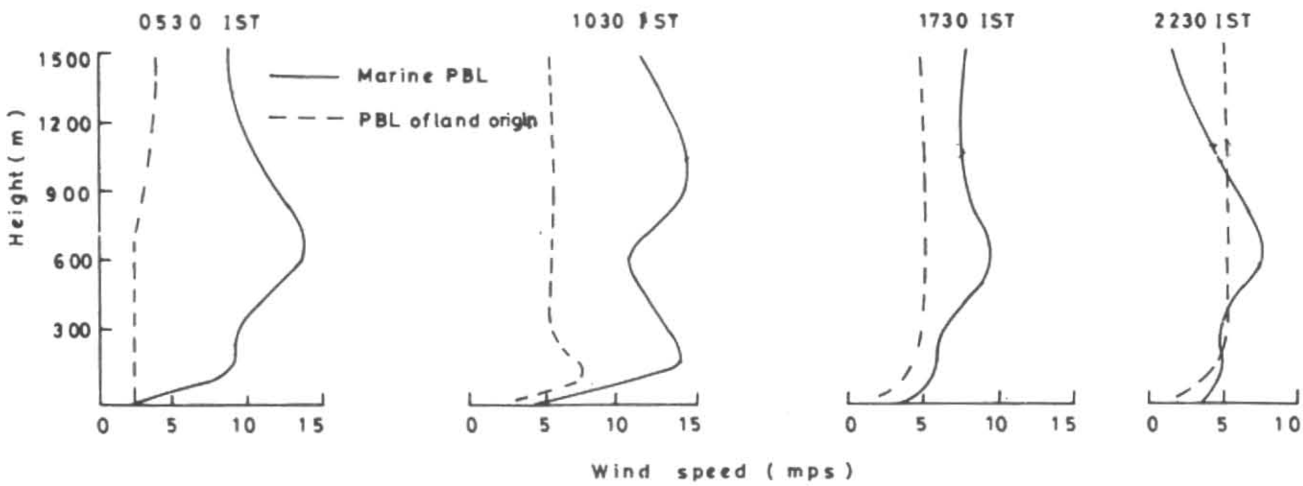


Fig. 8. Wind profiles associated with marine PBL (——) and PBL of land origin (— — —) during monsoon at Calcutta

and 6-7 July 1989. Vertical profiles of wind in the PBL on 1 and 2 July 1989 are presented in Fig. 8 to show the difference between the wind profiles associated with marine boundary layer and boundary layer of land origin. It was characterized by stronger winds, low level wind maximum, convective instability and absence of marked diurnal variability of the mixed layer characteristics.

4.2. *Patna*

Patna is an inland station representing the atmospheric conditions over the eastern part of the monsoon trough. Strength of the monsoon and diurnal cycle of heating are two important factors which determine the evolution of PBL in the monsoon trough region. The analysis of radiosonde data brings out that PBL in the night time is stable with a height of about 500 m and evolves as a shallow convective PBL by noon with PBL top extending up to 1500 m. Cloud layer deepens in the afternoon and evening hours raising the PBL height to 2500 m. Layer close to ground gradually becomes stable after sunset and by midnight stable PBL extends up to 500 m. Wind in the PBL did not reveal the presence of any wind maximum at Patna. During weak monsoon conditions, clouds are broken and sufficient ground heating takes place in cloud free areas during the day. It results in adiabatic lapse rate in the layer close to the ground and mixed layer develops as the day progresses. In the absence of heavy rains,

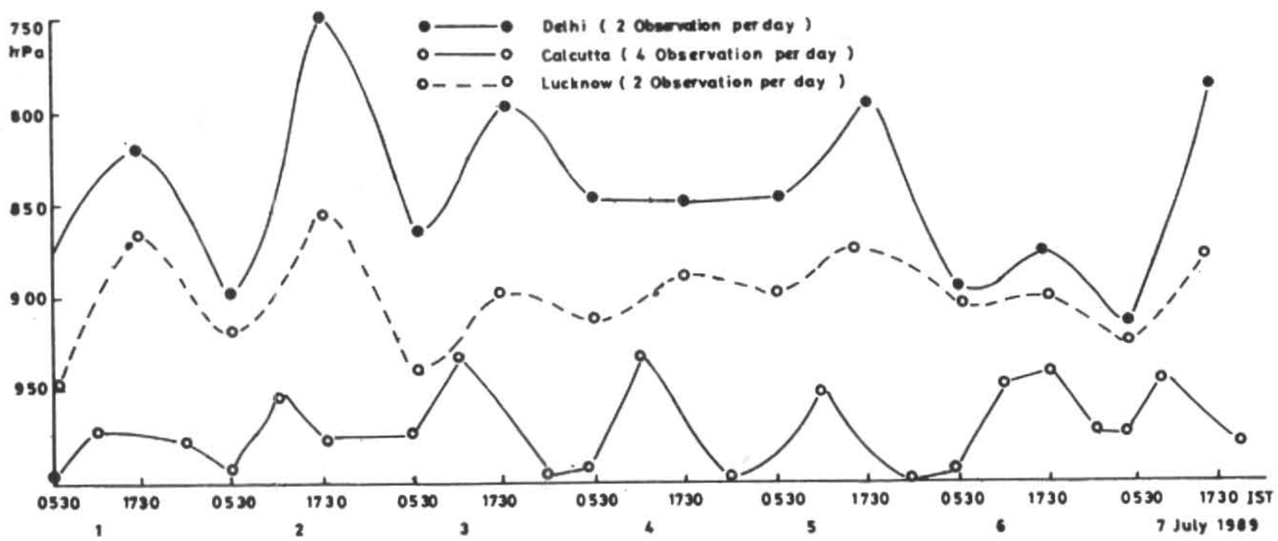


Fig. 9. Lifting condensation levels at different locations in the monsoon trough region

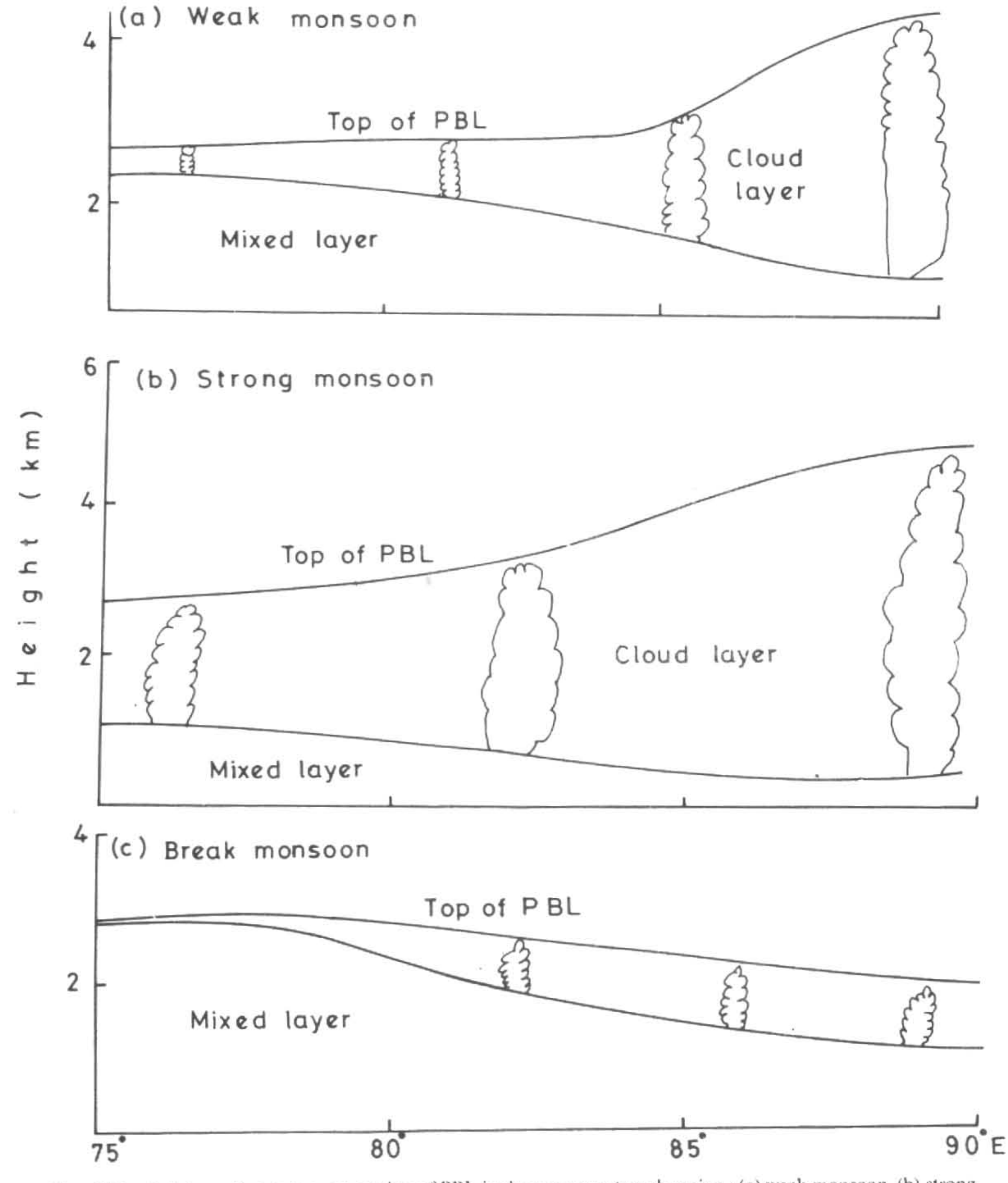
evaporation from the ground is minimum which leads to the decrease of moisture content with height in the mixed layer over the land. Monsoon air is observed above the mixed layer where clouds form. Complex interplay of convection due to the ground heating, synoptic convergence and strength of the monsoon current controls the change over from shallow convection to deep layer convection in this region.

4.3. *Delhi*

Characteristic features of the PBL at Delhi showed that winds were northwesterly in the lower levels becoming westerly with height. Normally southeasterly and southwesterly winds are associated with monsoon current at Delhi. During the period, a well developed dry convective PBL was observed at 1730 IST sounding up to 2.5-3.0 km. Since monsoon had entered only as feeble current over the region on 1 July 1989, dry northwesterlies were prevailing and conditions were more like pre-monsoon. During 1987, Sethuraman and others encountered similar situation in their boundary layer experiment at Delhi. PBL height observed during 1987 experiment at Delhi was 2700 m. It establishes that during weak or break monsoon conditions, PBL over western region of monsoon trough is likely to be of pre-monsoon type, in which dry convection predominates. Interesting feature observed in Delhi PBL is the absence of cloud layer. Mixed layer is topped directly by the stable layer. In night hours, inversion layer develops having a depth of about 500 m and a residual mixed layer persists aloft on many occasions. LCL levels at Delhi are found to be high (1.5-2.0 km) as compared to Calcutta and Lucknow (Fig. 9). It shows that mean value of LCL height during the period together with its diurnal variations increase westwards from Calcutta to Delhi.

5. Space cross-section of PBL

The PBL structure is continuously evolving in response to both diurnal heating cycle and to changing synoptic conditions. As a result, its structure and depth varies considerably over space and time. However, it is possible to generalize space cross-section of PBL for a given synoptic condition. Monsoon activity broadly falls into four synoptic conditions, *viz.*, active, normal, weak and break. It is to be noted that during period 1-7 July 1989, weak monsoon conditions were prevailing. Attempt is made here to construct space cross-section of PBL across Indo-Gangetic plains associated with weak monsoon with the help of radiosonde/slow rising balloon ascents taken at Calcutta, Bhubaneswar, Ranchi, Patna, Lucknow and Delhi. Schematic space



Figs. 10 (a-c). Schematic space cross-section of PBL in the monsoon trough region : (a) weak monsoon, (b) strong monsoon, and (c) break monsoon

cross-section of PBL across the Indo-Gangetic plains during the weak monsoon conditions is presented in Fig. 10(a) and characteristic features of PBL at different location are summarized in Table 2. It is seen that over West Bengal, Bihar, Orissa and east Madhya Pradesh region (eastern parts of monsoon trough), mixed layer is stable with high moisture content, low LCL and deep cloud layer. The height of mixed layer and LCL increases westward and the depth of cloud layer and moisture content decreases. On reaching western parts of monsoon trough region, *i.e.*, over Rajasthan, Punjab, Haryana and adjoining areas, PBL becomes unstable with deep mixed layer. High LCL and low moisture content are characteristic features of PBL in this region

TABLE 2

PBL characteristics at different stations in the monsoon trough region
7 July 1989 (1730 IST)

Station	Characteristics					
	LCL (m)	Temp. lapse rate (°C/100 m)	Sp. humidity lapse rate [(gm/kg)/100 m]	Mean Sp. humidity (Surface-850 hPa layer) (gm/kg)	Stability	PBL type
Delhi	1900	1.00	0.85	12	Unstable	Dry convective
Lucknow	1000	0.66	0.80	169	Conditionally unstable	Shallow convective
Pendra	500	0.57	0.31	199	Do.	Monsoon
Calcutta	300	0.41	0.27	22	Stable	Do.

during weak monsoon condition. Change from one synoptic condition to another during the season is associated with changes in airmass and PBL characteristics. Active monsoon is heralded by strengthening of monsoon winds and associated changes in PBL structure. Schematic space cross-section of PBL structure during active monsoon condition is shown in Fig. 10(b). Monsoon PBL extends up to Rajasthan on such occasions. Mixed layer in this case is statically stable with shallow depth. Moisture content is high and LCL is at a lower height well within the mixed layer. Cloud layer is quite deep and in the areas of vigorous monsoon, it may extend to upper troposphere. During break monsoon, airmass is replaced by drier continental air. Dry convective PBL is expected to develop over Rajasthan, Punjab, Haryana, Delhi, west Uttar Pradesh and adjoining Madhya Pradesh and shallow convective PBL over eastern parts of the monsoon trough. Space cross-section of PBL over the Indo-Gangetic plains during break monsoon is shown in Fig. 10(c). During break monsoon situation, deep cumulus clouds over the east Uttar Pradesh, Bihar and West Bengal found in case of monsoon PBL are replaced by fair weather strato-cumulus.

6. Conclusions

Based on the results discussed earlier, the following conclusions may be drawn :

(i) PBL structure in the monsoon trough region shows wide temporal and spatial variations depending upon the strength of monsoon current. Based on the discontinuities in the vertical gradients of thermodynamical parameters mainly three types of boundary layers, *viz.*, monsoon PBL, shallow convective PBL and dry convective PBL have been identified in the monsoon trough region.

(ii) Monsoon boundary layer over land is made up of layered structure consisting of mixed layer, cloud layer and inversion/isothermal layer. However, the presence or absence of transition layer could not be ascertained in this study.

(iii) Mixed layer of the monsoon PBL is of 400-500 m deep and characterized by similar vertical profiles of virtual potential temperature and specific humidity. LCL is very low (100-300 m) and lies well within the mixed layer. Mixed layer is topped by a deep cloud layer of 2000-3000 m thickness. Lapse rate of virtual potential temperature in the cloud layer is found to be about 0.4°C/100 m and specific humidity shows slight decrease with height. Further, this layer is found to be both statically and convectively unstable. Inversion/isothermal layer having virtual potential temperature lapse rate of 0.9°C/100 m is found above the cloud layer. On occasions when monsoon current is strong, cloud layer extends from 100 m to the middle of the troposphere and it becomes difficult to locate mixed layer.

(iv) Shallow convective PBL displays a marked layer structure. In this case, LCL is found at relatively higher levels (450 m). Cloud layer is shallow with thickness varying 700-1000 m. Sharp decrease of moisture takes place above the cloud layer and a marked diurnal variation in the stability of the mixed layer is observed.

(v) Dry convective PBL is characterized by deep mixed layer with very high LCL (1500-2000 m) with an absence of cloud layer altogether. Mixed layer is directly topped by an isothermal/stable layer. Marked diurnal variation in the static stability of the lower half of the mixed layer is observed.

(vi) Typical space cross-sections of the PBL over the Indo-Gangetic plains have been developed for active, weak and break monsoon conditions. It is found that at a given location, transition from one type of boundary layer to another is largely governed by the complex interplay of the synoptic vergence, strength of the monsoon current and local convection.

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