

Thermodynamic structure of the atmosphere along East coast of India during BOBMEX-99

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(Received 1 April 2003, Modified 23 August 2004)

सार – इस शोध-पत्र में भारत के पूर्वी तटीय क्षेत्रों के प्रबल सिनॉप्टिक स्केल मौसम विक्षोभों के लिए वर्ष 1999 की ग्रीष्मकालीन ऋतु की संवहनी परिसीमा स्तर (सी.बी.एल.) की तापगतिकीय विशेषताओं की जाँच की गई है। इस कार्य के लिए पूर्वी तट के छः केंद्रों की तीव्र प्रेक्षण अवधियों (आई. ओ. पी.) के बंगाल की खाड़ी मानसून प्रयोग-99 के दौरान विशेष रूप से एकत्रित किए गए उच्च विभेदन वायु वैज्ञानिक प्रेक्षणों पर विचार किया गया है। उपलब्ध पाँच आई. ओ. पी. प्रेक्षणों में से दो प्रेक्षणों का उपयोग, एक जुलाई के दौरान और अन्य अगस्त 1999 के दौरान सी. बी. एल. की विशेषताओं की विभिन्नताओं का अंवेक्षण करने के लिए किया गया है। धरातलीय दाब वितरण और केंद्रों के स्थान के आधार पर तटीय केंद्रों को दो वर्गों, प्रबल मौसम विक्षोभ (या तो गहन अवदाब अथवा निम्न दाब क्षेत्र) जैसे श्रेणी “ए” केंद्र (धरातल के निम्न सतह दाब के विक्षोभ के समीप स्थित केंद्र) और श्रेणी “बी” केंद्र (विक्षोभ और उच्च सतह दाब से संबद्ध दूर स्थित केंद्र) में वर्गीकृत किया गया है। अगस्त के महीने में धरातल के विभिन्न तापगतिकीय प्राचल की स्थानिक परिवर्तनशीलता से धरातल पर अधिक नमी वाली संवहनी सक्रियता का पता चलता है। जुलाई और अगस्त दोनों महीनों के दौरान विभिन्न तापगतिकीय प्राचलों के औसत से उर्ध्वाधर प्रोफाइलों से श्रेणी “बी” की अपेक्षा श्रेणी “ए” के केंद्रों में अधिक संवहनी सक्रियता का पता चला है जिससे विक्षोभ के समीप स्थित केंद्रों पर विद्यमान विक्षोभ के अधिक प्रभावी होने का पता चलता है। तथापि दो वर्गों की सतह के स्तर को छोड़कर नमी वाली संवहनी सक्रियता अगस्त की अपेक्षा जुलाई के महीने में अधिक होती है। सी.बी.एल. का ऊपरी सिरा 700–500 है. पा. के बीच परिवर्तनशील में अधिक होता है। सुनिश्चित परिवर्तनशील आरेखों से जुलाई और अगस्त के महीनों के दौरान सभी वर्गों में इकहरी मिश्रित रेखा संरचना का पता चलता है।

ABSTRACT. Thermodynamic features of the Convective Boundary Layer (CBL) during the summer monsoon season of 1999 have been examined over the Indian east coastal stations with respect to the prevailing synoptic scale weather disturbances. For this purpose high resolution aerological observations specially collected during the Bay of Bengal Monsoon Experiment-99 for the Intensive Observing Periods (IOPs) for the six east coastal stations have been considered. Out of the five available IOPs observations during two IOPs, one during July and another during August, 1999, have been used to explore the differences in the CBL characteristics. The coastal stations are categorized into two groups based on the surface pressure distribution and the location of the stations with respect to the prevailing weather disturbance (either deep depression or low pressure area) viz., Gr.A (stations located in the vicinity of the disturbance with low surface pressure) and Gr.B (stations situated away from the disturbance and associated with high surface pressure) stations. The temporal variation of different thermodynamic parameters at the surface indicated more moist convective activity at the surface during August. The averaged vertical profiles of different thermodynamic parameters revealed more convective activity for Gr.A stations as compared to Gr.B stations during both July and August indicating the more influence of the existing disturbance on the stations situated in the proximity of the disturbance. However, the moist convective activity is more during July as compared to August, except in the surface layer, for both the groups. The CBL tops vary in the range 700-500 hPa. The conserved variable diagrams revealed single mixing line structure during both July and August for all the categories.

Key words – Convective boundary layer, Bay of Bengal Monsoon Experiment, Monsoon boundary Layer, East coastal stations, Thermodynamic features of the CBL, Summer monsoon season.

1. Introduction

The Bay of Bengal is considered to be a critical area as far as Indian monsoon is concerned. The monsoon is

strongly coupled to the warm oceans surrounding the Indian subcontinent and Bay of Bengal is among one of them. Most of the monsoon rainfall occurs in association with synoptic-scale systems, that is, the monsoon

disturbances, which are generated over these waters and move onto the Indian landmass (Bhat *et al.*, 2001b). However, there have been very few atmospheric observations conducted over the Bay of Bengal regions during the summer monsoon season. Therefore, with this view, the first observational programme entitled 'Bay of Bengal Monsoon Experiment (BOBMEX)' was conducted over the Bay of Bengal during July-August, 1999. The BOBMEX-99, a field experiment, was conducted under the Indian Climate Research Programme. The more information regarding the BOBMEX-99 *viz.*, design of the experiment, objectives, instruments and initial results are given elsewhere (Bhat *et al.*, 2001a; Bhat & Ameenulla, 2000; Bhat *et al.*, 2000; Sikka & Sanjeeva Rao, 2000 and Bhat, 2001).

Under BOBMEX-99 atmospheric and oceanographic observations were collected during 16 July to 30 August 1999 in two phases over the Bay of Bengal region from multiple platforms. During the same period special high resolution aerological observations were also undertaken for Indian east coastal stations and for an island station. These observations were collected by India Meteorological Department at the respective observational sites for the Intensive Observation Periods (IOPs). The emphasis of BOBMEX-99 was to collect high quality data during different phases of convection over the Bay of Bengal, which can be used to understand the vertical stability of the atmosphere and further to investigate the vertical structure of the atmospheric boundary layer.

Convective processes are responsible for the transport of heat and moisture from surface to the atmosphere above. They are among the major factors which bring variability in the weather. The effect of the convective processes on the surrounding environment must be understood in order to study the role of convection. During the summer monsoon season convection, either dry or moist, is always present in the atmosphere (Betts and Albrecht, 1987). Hence, in the present study the atmospheric boundary layer is more precisely referred as Convective Boundary Layer (CBL). The vertical structure of the CBL over the land and oceanic regions has been explored by many workers (Morwal, 1998; 2000; 2002; 2003; Morwal and Seetaramayya, 2003; Parasnis and Morwal, 1991; 1993; Betts, 1982, Betts and Ridgeway, 1989; Kloesel and Albrecht, 1989).

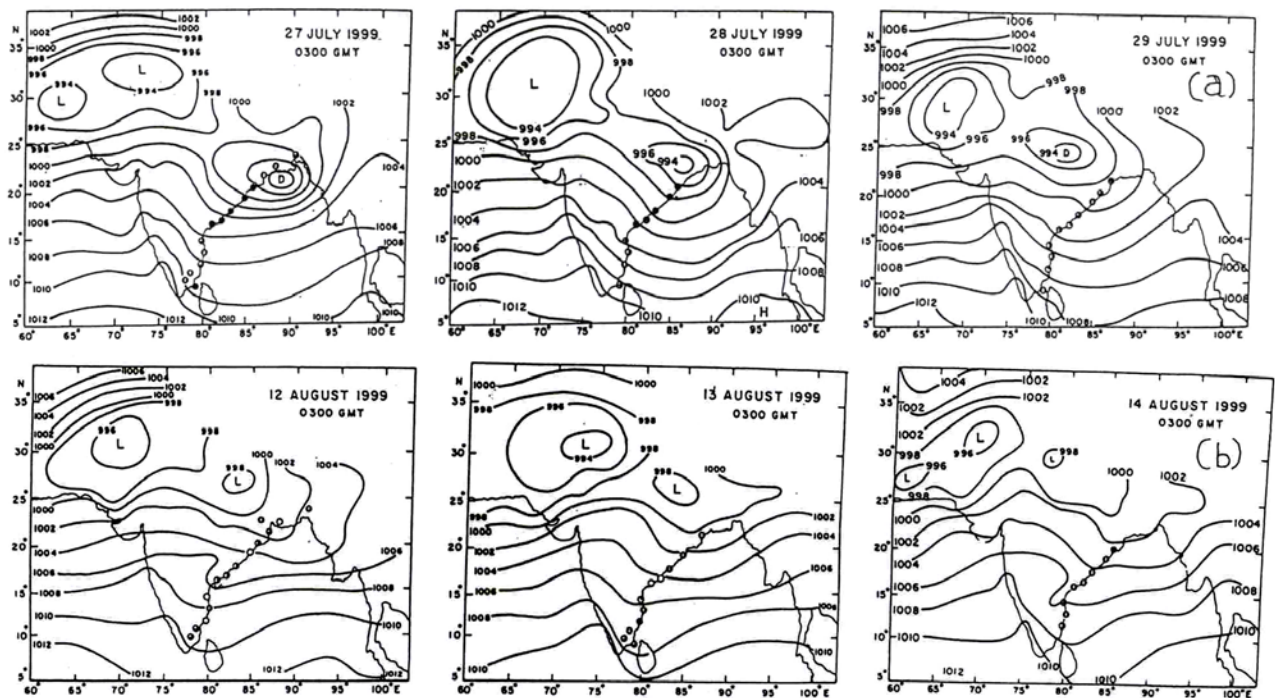
The vertical structure of the atmospheric boundary layer in the tropical Atlantic and Pacific Oceans has been extensively studied (Riehl *et al.*, 1951; Malkus, 1956; Augstein *et al.*, 1974 and Brummer *et al.*, 1974). However, very little is known about the same over the Arabian Sea, Bay of Bengal and the Indian Ocean. The



Fig. 1. Location of the Indian east coastal stations and island station Port Blair (denoted by closed circles)

radiosondes from the ships and the dropsondes from the aircraft taken during the International Indian Ocean Expedition, for the first time, provided the vertical stratification of the temperature and moisture present in the lower troposphere over the region north of 10° N in the Arabian Sea. The data revealed the presence of a sharp temperature inversion in the layer 900-750 hPa over the western and central regions of the Arabian Sea, with a dry and warm air mass prevailing above (Colon, 1964; Sikka and Mathur 1965; Desai, 1968, 1970). Further, the investigations conducted by Pant (1978) utilizing the data set collected through Indo-Soviet Monsoon Experiment-1973 (ISMEX) in the west Indian Ocean and the Arabian Sea revealed that in the region north of 10° N in the Arabian Sea, a strong temperature inversion tops the boundary layer and shows a downward slope from the coast of India towards the west. In the extreme eastern Arabian Sea region, strong convective mixing weakens the layered structure and leads to the destruction of the inversion.

In the past, over the Bay of Bengal region, there have been three major field experiments which were conducted during the summer monsoon season *viz.*, MONSOON-77, MONEX-79 and MONBLEX-90. Through these experiments the data was collected either over the head



Figs. 2(a&b). Surface pressure charts (a) 27-29 July 1999 and (b) 12-14 August 1999

Bay of Bengal regions or over the monsoon trough regions and no attention was given to stations situated along the east coast of India. For the first time, the aerological observations have been made available for the east coastal stations during the summer monsoon of 1999 through BOBMEX-99.

In the present paper the data collected for the east coastal stations have been utilized to explore the characteristic features of the CBL during the BOBMEX-99 observational period. An attempt has been made to examine the spatial and temporal variation of the different thermodynamic parameters in the CBL. The purpose of this paper is to examine the effect of synoptic scale weather disturbances, *i.e.*, deep depression (27-29 July) and low pressure area (12-14 August), which are of different intensity, over the stations located along the Indian east coast. Also, an attempt has been made to bring out the differences in the thermodynamic parameters for the stations situated in the vicinity of the disturbance and located away from the disturbance during these two IOPs.

2. Location of observations and meteorological conditions

During the BOBMEX-99 field programme aerological observations were collected along the Indian

east coast for six land stations *viz.*, Kolkata ($22^{\circ} 39' N$, $88^{\circ} 27' E$, 6 m asl), Bhubaneswar ($20^{\circ} 15' N$, $85^{\circ} 50' E$, 46 m asl), Visakhapatnam ($17^{\circ} 43' N$, $83^{\circ} 14' E$, 3 m asl), Machilipatnam ($16^{\circ} 11' N$, $81^{\circ} 08' E$, 3 m asl), Chennai ($13^{\circ} N$, $80^{\circ} 11' E$, 16 m asl) and Karaikal ($10^{\circ} 55' N$, $79^{\circ} 56' E$, 7 m asl) and an island station in the Andaman and Nicobar islands *viz.*, Port Blair ($11^{\circ} 40' N$, $92^{\circ} 43' E$, 79 m asl). The location of these stations (shown by solid circles) is shown in Fig. 1.

Fig. 2(a) shows the surface pressure charts for 27, 28 and 29 July 1999 at 0300 UTC. From this figure it is seen that there was a depression over northwest Bay and adjoining West Bengal coast on 27th July and it further intensified into a deep depression in the evening of 27th July and lay centered at Lat. $21.0^{\circ} N$, Long. $88.5^{\circ} E$. It crossed Orissa – West Bengal coast in the morning of 28th July and lies as a deep depression centered at 0300 UTC near Lat. $23.0^{\circ} N$, Long. $86.5^{\circ} E$. It moved in northwesterly direction and weakened into a depression. It further moved in westnorthwesterly direction and lies very close to Satna in NE Madhya Pradesh. Associated cyclonic circulation extends up to mid tropospheric levels. The axis of the monsoon trough lies south of its normal position. The trough on sea level chart from south Maharashtra coast to Kerala coast persists on all the three days.

TABLE 1

Station wise distribution of the radiosonde observations collected during BOBMEX-99

| S. No. | Station | Sounding available | Sounding during IOPs |
|--------|---------------|--------------------|----------------------|
| 1. | Kolkata | 118 | 63 |
| 2. | Bhubaneswar | 126 | 64 |
| 3. | Visakhapatnam | 126 | 64 |
| 4. | Machilipatnam | 113 | 50 |
| 5. | Chennai | 118 | 63 |
| 6. | Karaikal | 105 | 28 |
| | Total | 706 | 332 |

TABLE 2

Station wise distribution of the radiosonde observations collected during IOP2 and IOP4

| S. No. | Station | IOP2 (27-29 July 1999) | IOP4 (12-14 August 1999) |
|--------|---------------|---------------------------|-----------------------------|
| 1. | Kolkata | 7 | 12 |
| 2. | Bhubaneswar | 12 | 12 |
| 3. | Visakhapatnam | 4 | 12 |
| 4. | Machilipatnam | 8 | 12 |
| 5. | Chennai | 5 | 11 |
| 6. | Karaikal | 8 | 12 |
| | Total | 44 | 71 |

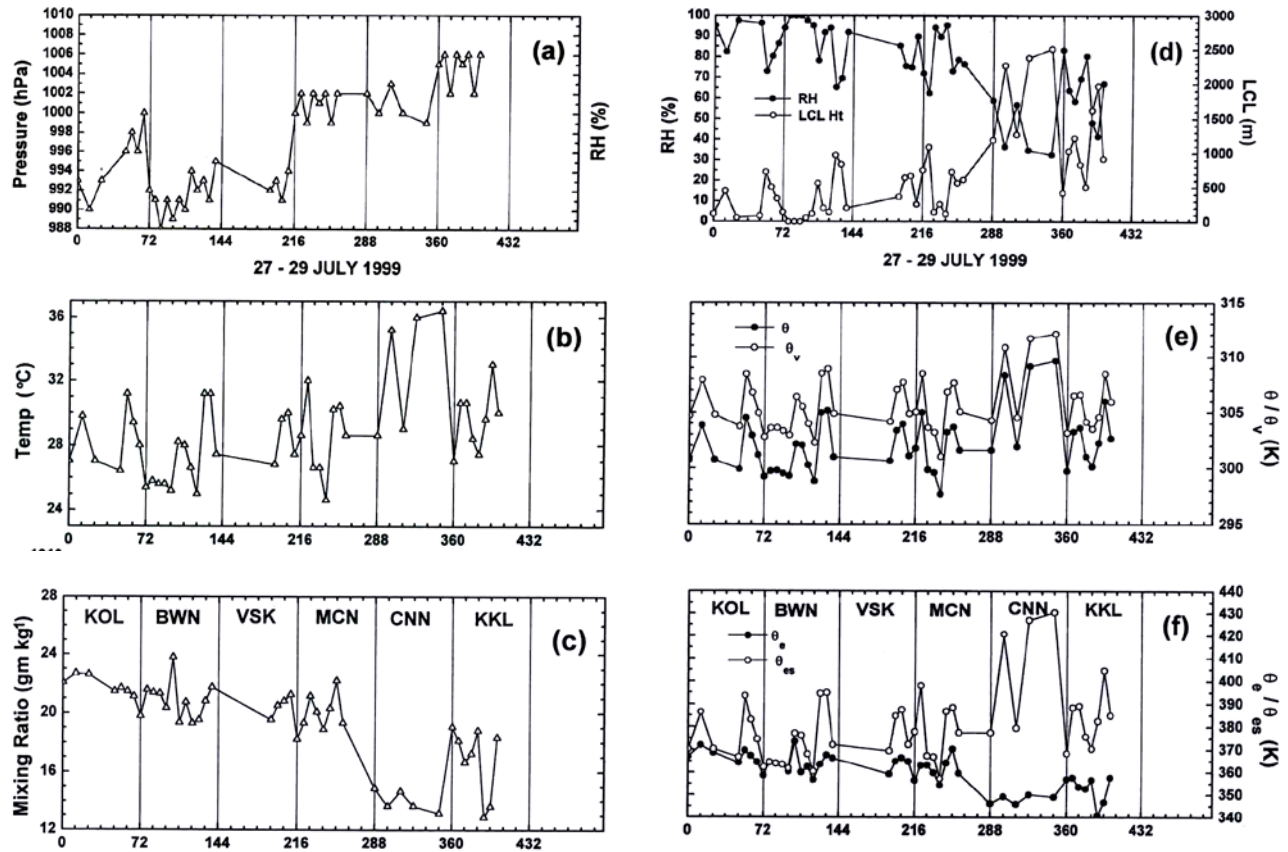
The prevailing synoptic weather conditions on 12, 13 and 14 August 1999 at 0300 UTC is shown in Fig. 2(b). In Fig. 2(b) it is seen that on 12th August, the low pressure area lies over northeast Uttar Pradesh and adjoining Bihar plains. Associated cyclonic circulation extends up to 1.5 km asl. The western disturbance as an upper air system lies over north Pakistan and adjoining parts of Jammu and Kashmir on 12th and 13th August 1999. An induced low pressure area has formed over Punjab and neighbourhood and associated cyclonic circulation extends up to 1.5 kms asl, which moved northeastwards across Himachal Pradesh on 14th August 1999. The axis of monsoon trough on sea level charts passes through Ferozpur, Bareilly, Patna and Tezu on 14th August. Another branch runs from Patna to Kolkata and thence southeastwards to east central Bay.

Thus, the prevailing weather conditions over the observational area and neighbourhood reveal that the period IOP2 (*i.e.*, July period) is characterized by a deep depression associated with the southward shift of the monsoon trough and during IOP4 (*i.e.*, August period) there existed a low pressure area which was associated with the northward shift of the monsoon trough along the foothills of Himalayas. The north-south shift of the monsoon trough has an important bearing with the rainfall distribution over India (Parasnis *et al.*, 1991). Mean trough line runs at surface approximately parallel to the southern edge of Himalaya Mountain and exhibits periodic movement to the north and south of its normal position. Under the normal monsoon conditions, the axis of the monsoon trough extends from Ganganagar to Kolkata with its eastward end over the Head Bay. The normal position of monsoon trough is usually associated

with enhanced monsoon activity over India (Rao, 1976; Sikka and Narasimha, 1995). Thus, when the axis of the trough moves north and lies close to the Himalaya, rainfall weakens over most of north India (a condition characteristic of break in monsoons, although widespread and heavy rains occur in the northeast, the Himalayan foothills and the southeast peninsula); correspondingly when the trough moves south there tends to be heavy rains in the north Indian plain and the monsoon becomes active with the opposite trend in the other areas (Rajkumar and Narasimha, 1997).

3. Data and method of analysis

Special high resolution aerological observations were collected for the six Indian east coastal stations *viz.*, Kolkata (KOL), Bhubaneswar (BWN), Visakhapatnam (VSK), Machilipatnam (MCN), Chennai (CNN) and Karaikal (KKL). Daily four 6-hourly (0000, 0600, 1200 and 1800 UTC radiosonde ascents are available during the Intensive Observation Periods (IOPs) for all the above mentioned east coast stations. During the BOBMEX-99 observational period *i.e.*, 16 July to 30 August 1999, there were in all five Intensive Observing Periods (IOPs) *viz.*, IOP1 (20 – 22 July), IOP2 (27 – 29 July), IOP3 (4 - 5 August), IOP4 (12 – 14 August) and IOP5 (20 – 28 August). Table 1 gives the stationwise distribution of the number of radiosonde observations undertaken and the number of radiosonde observations belonging to all the IOPs for all the six stations. Thus, out of 706 observations in all 332 radiosonde profiles were collected during the different IOPs over land stations. However, in this paper the observations collected during IOP2 and IOP4 have been utilized because during these periods the data is available for all the above mentioned stations



Figs. 3(a-f). Daily march of the surface parameters during IOP2 (27-29 July 1999) for the stations Kolkata (KOL), Bhubaneswar (BWN), Vishakhapatnam (VSK), Machilipatnam (MCN), Chennai (CNN) and Karaikal (KKL). (a) Surface pressure (b) Air temperature (c) Mixing ratio (d) Relative humidity and Lifting Condensation Level (LCL), (e) Potential temperature (θ) and Virtual potential temperature (θ_v) and (f) Equivalent potential temperature (θ_e) and Saturated equivalent potential temperature (θ_{es})

simultaneously. Total 44 and 71 radiosonde ascents were taken during IOP2 and IOP4 respectively. Table 2 gives the stationwise distribution of the data for both the IOPs.

For each radiosonde ascent the vertical profiles of temperature (T , K) and dew point temperature (T_d , K) have been considered from surface up to 400 hPa at an interval of 25-30 hPa. Each individual radiosonde dataset is subjected to linear interpolation in order to get the values of T and T_d at an interval of 10 hPa from surface up to 400 hPa level. The stations (total six stations) located along the east coast are categorized into two groups depending on the distribution of the surface pressure and the distance of the station from the centre of the prevailing synoptic scale weather disturbances *viz.*, low pressure area (LPA)/deep depression (DD) over the observational region and neighbourhood. The stations located in the vicinity of the centre of the disturbance are found to be

associated with the low values of surface pressure and categorized as Gr. A stations. The stations positioned away from the centre of the disturbance are appeared to be associated with the high values of surface pressure and are categorized as Gr. B stations. Gr. A includes the stations Kolkata (KOL), Bhubaneswar (BWN) and Visakhapatnam (VSK) whereas in Gr. B stations Machilipatnam (MCN), Chennai (CNN) and Karaikal (KKL) are included. For each IOP, groupwise 6-hourly (0000, 0600, 1200 and 1800 UTC) averaged vertical profiles of T and T_d at an interval of 10 hPa have been computed. Also, for each IOP of 3-day period groupwise averaged vertical profiles of T and T_d have been computed.

All the averaged vertical profiles of T and T_d , as mentioned above, have been used to compute the different thermodynamic parameters such as potential temperature (θ , K), virtual potential temperature (θ_v , K), mixing ratio

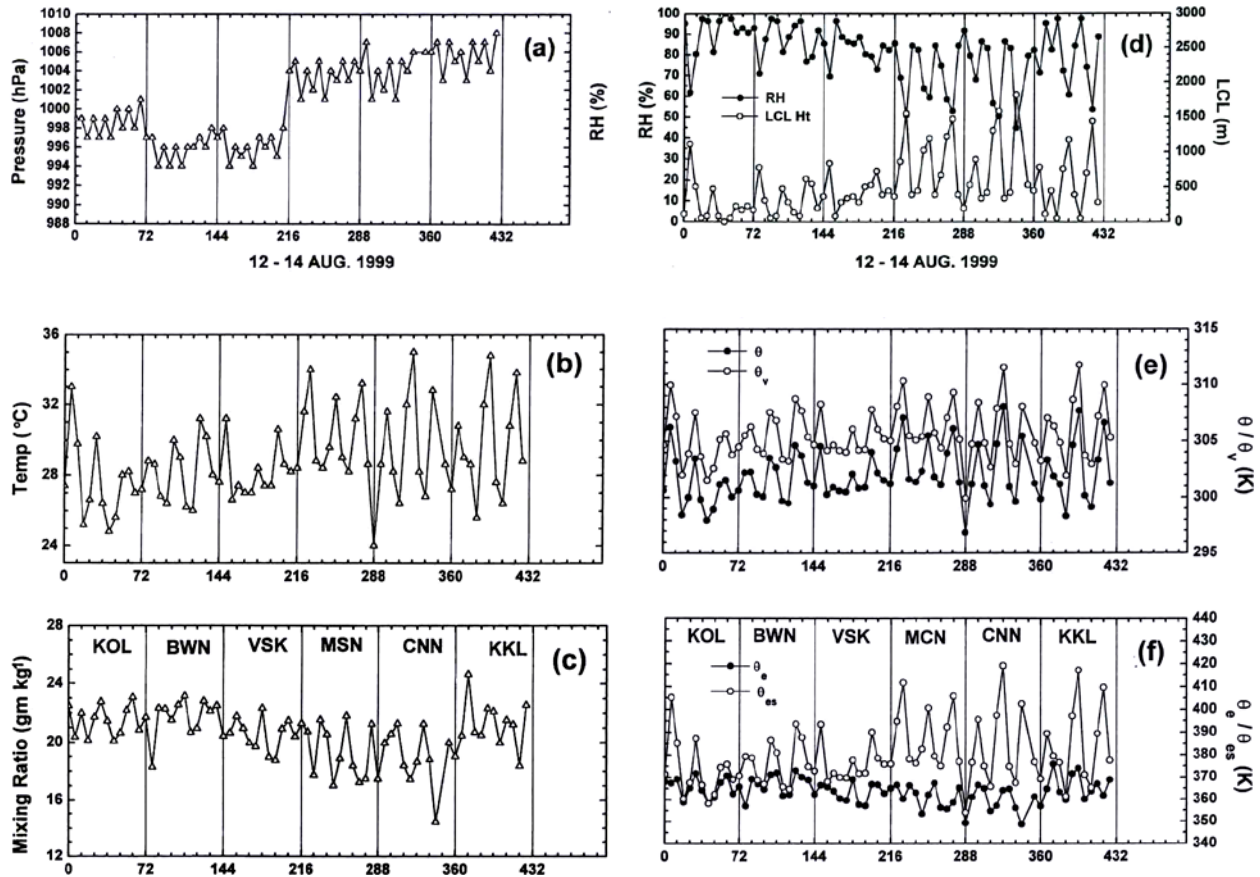


Fig. 4(a-f). Same as Figs. 3(a-f) during the IOP4 (12-14 August 1999)

(q , gm kg^{-1}), relative humidity (RH, %), equivalent potential temperature (θ_e , K), saturated equivalent potential temperature (θ_{es} , K), saturation level pressure (p_{SL} , hPa) and saturation pressure deficit (P^* i.e., $p_{SL}-p$, hPa) from surface up to 400 hPa level at an interval of 10 hPa. P^* represents the lack of saturation in the layer p to p_{SL} and is a very useful parameter to delineate the different sub layers in the CBL (Morwal, 2003). Higher negative values of P^* are associated with the unsaturated layers and it is positive in the cloudy layers (Morwal and Seetaramayya, 2003). Also, 6-hourly temporal distribution of surface parameters (reported at the time of radiosonde ascent) such as pressure (p), temperature (T), mixing ratio (q), relative humidity (RH), lifting condensation level (LCL), potential temperature (θ), virtual potential temperature (θ_v), equivalent potential temperature (θ_e) and saturated equivalent temperature (θ_{es}) etc. have been given for observational period of both the IOPs during July (IOP2) and August (IOP4).

Near-surface air has modest negative buoyancy if lifted into the lowermost troposphere, below its level of free convection (LFC). The work done to lift air through this layer of negative buoyancy is called as Convection inhibition energy (CINE). Above the LFC, the air experiences positive buoyancy (Mapes, 2000) and the parcel is lifted moist adiabatically. Thus Convective Available Potential Energy (CAPE) is the work done by this positive buoyancy force on a parcel lifted from level of free convection, moist adiabatically, till the level of neutral buoyancy. Deep clouds can develop by the ascent of air from a given level only if its CAPE is greater than zero. Low values of CINE imply a favourable condition for convection and large values are associated with an increased barrier to convection (Bhat *et al.*, 2001a).

Using the vertical profiles of T and T_d the instability parameters viz., CAPE (kJ kg^{-1}) and CINE (J kg^{-1}) have been computed for each radiosonde ascent for all the east

coastal stations during IOP2 and IOP4 utilizing the method described by Williams and Renno (1993) and used by Bhat *et al.* (2001a) and Roy and Bhowmik (2003). In some cases CAPE could not be obtained as the data is not available up to higher levels. Condensations, precipitation, freezing of liquid water and level of parcel origin, influence the virtual temperature of the air parcel and hence CAPE and CINE, as the parcel undergoes undiluted ascent in the atmosphere (Emanuel, 1994).

4. Results and discussion

The results of the investigation for the two IOPs, one falling in July (IOP2) and the other in August (IOP4), have been discussed at the surface for each individual station. At the end of this discussion the results obtained utilizing the instability parameters such as CAPE and CINE computed at the surface air have been presented. In the vertical levels the given discussion is based on different groups (from surface up to 400 hPa only). Also, in order to reveal the variations in the CBL structure due to presence of synoptic scale weather disturbances of different intensity the mean structure during the two IOPs (one each during July and August) have been discussed. Further, to emphasize the influence of the prevailing synoptic scale disturbances over various stations located at different places (*i.e.*, spatial distribution) the CBL characteristics are compared between the two categories of stations *i.e.*, Gr. A and Gr. B. The results are presented in different sub sections as given below.

Daily variation of surface parameters

Even though duration of observation for both the IOPs is same, *i.e.*, 3 days, the total number of aerological observations available during IOP4 is more (total 71) as compared to that during IOP2 (in all 44). However, the observations are sufficient to explore the day-to-day variations during the above IOPs. Figs. 3(a-f) and Figs. 4(a-f) show the temporal variation of surface parameters such as (a) pressure, (b) temperature, (c) mixing ratio, (d) LCL and RH, (e) θ and θ_v , and (f) θ_{es} and θ_{es} for IOP2 and IOP4 respectively for all the east coast stations. Vertical line demarks the different stations starting from Kolkata (KOL) to Karaikal (KKL). The time scale (cumulative 0 to 500 hrs.) is indicated on the X-axis which varies from 0 to 72 (*i.e.*, 3 days) hours for each station.

From Fig. 3(a) and Fig. 4(a) it is seen that the surface pressure, in general, is lower for the Gr. A stations as compared to that for Gr. B stations during both the IOPs.

This is in support of the results obtained by Bhat *et al.* (2001b) over the Bay of Bengal region. This may possibly be due to the influence of the prevailing synoptic scale disturbances and also due to the north-south gradient in pressure. However, the pressure is found to be low during July (*i.e.*, IOP2) due to the presence of deep depression and comparatively high during August (*i.e.*, IOP4) due to observed low pressure area which is a weak system as compared to deep depression. The semi-diurnal variation in surface pressure values is clearly evident for all the stations during both the IOPs. For Gr. A stations during both the IOPs pressure is lower over Kolkata, Bhubaneswar and Vishakhapatnam. The pressure is high for the stations located south of Visakhapatnam *i.e.*, for the Gr. B stations *viz.*, Machilipatnam, Chennai and Karaikal.

The temperature [Figs. 3(b) and Fig. 4(b)] shows diurnal variation for all the stations during both the IOPs. In general, the temperature increases southward from Kolkata to Chennai. The temperatures are low for the stations Kolkata, Bhubaneswar and Visakhapatnam as compared to that over the stations Machilipatnam, Chennai and Karaikal. During IOP2 the temperature at Chennai is very high in comparison to other stations and also compared to that over Chennai during IOP4. The mixing ratio [Fig. 3(c) and Fig. 4(c)] also shows diurnal variation at the surface. Over Kolkata, Bhubaneswar and Vishakhapatnam the mixing ratio is more as compared to that of the stations south of Visakhapatnam. However, it shows steady decreasing trend southward from Bhubaneswar to Chennai. The values at Chennai are very low during IOP2. Thus at the surface the air is cool and moist over Gr. A stations and comparatively warm and dry over Gr. B stations. This difference in the surface values of temperature and mixing ratio may be the combined influence of the observed synoptic scale disturbances and due to the inherent south-north gradient in these parameters during the summer monsoon season.

[Fig. 3(d) and Fig. 4(d)] show the relative humidity and height of the lifting condensation level for IOP2 and IOP4 respectively for all the stations. At the surface the RH is found to be higher during IOP4 as compared to IOP2. For both the IOPs Gr. A stations (KOL, BWN and VSK) show high RH as compared to Gr. B stations (MCN, CNN, and KKL). It is seen that in most of the cases RH is more than 80% over Gr. A stations and for Gr. B stations it is less than 80% for many occasions. From [Fig. 3(d) and Fig. 4(d)] inverse relationship is clearly evident between RH and LCL height. In general, the LCL height is less for Gr. A stations as compared to

TABLE 3

Average values of different surface parameters and range of variation for Gr. A and Gr. B stations during IOP2 and IOP4

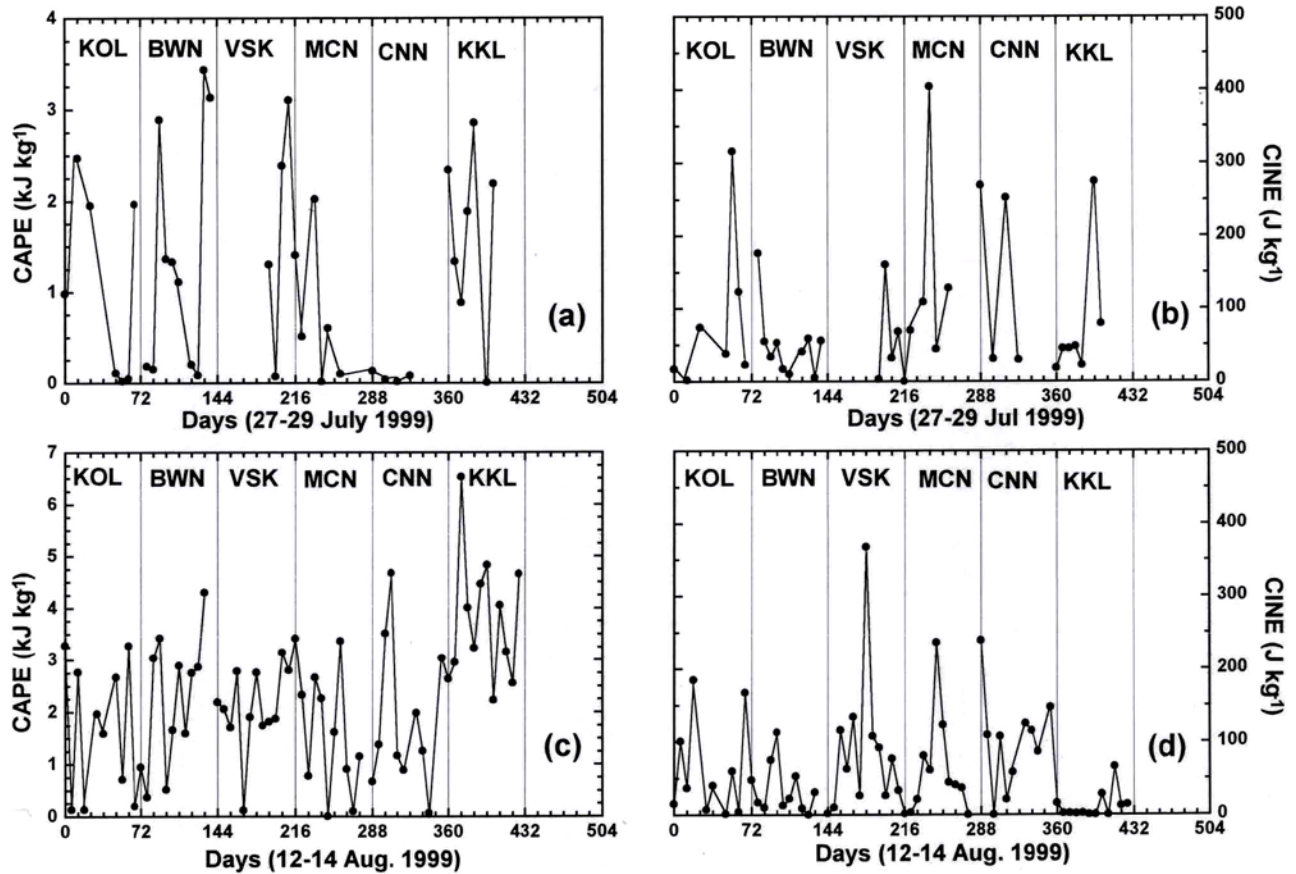
| Surface parameter (Range of variation) | IOP2 (27-29 July 1999) | | IOP4 (12-14 August 1999) | |
|---|---------------------------|------------------------|-----------------------------|------------------------|
| | Gr. A | Gr. B | Gr. A | Gr. B |
| Pressure (hPa) | 992.7 (988-1000) | 29.5 (24.6-36.4) | 28.0 (24.8-33.0) | 29.4 (24.0-35.0) |
| Temperature (°C) | 27.7 (25.0-31.2) | 29.5 (24.6-36.4) | 28.0 (24.8-33.0) | 29.4 (24.0-35.0) |
| Mixing ratio (g kg ⁻¹) | 21.1 (19.3-22.7) | 18.0 (12.9-21.1) | 21.3 (18.3-23.2) | 19.7 (14.4-24.7) |
| RH (%) | 87.6 (65-100) | 69.3 (33-95) | 87 (62-100) | 76 (45-98) |
| LCL (m) | 322 (0-974) | 920 (112-2512) | 333 (0-1114) | 679 (56-1814) |
| θ (K) | 301.5 (298.9-305.2) | 302.6 (297.7-309.7) | 301.4 (298.0-306.3) | 302.2 (296.8-308.1) |
| θ_v (K) | 305.3 (302.3-308.9) | 305.8 (301.0-312.1) | 305.2 (301.5-310.0) | 305.8 (299.9-311.7) |
| θ_e (K) | 364.8 (356.7-373.5) | 356.5 (340.8-370.3) | 365.2 (357.0-373.0) | 361.4 (348.7-375.9) |
| θ_{es} (K) | 374.7 (360.4-394.5) | 383.8 (357.2-430.5) | 375.4 (358.3-405.2) | 382.5 (354.0-419.2) |
| CAPE (kJ kg ⁻¹) | 1.259 (0.019-3.429) | 0.760 (0.003-2.855) | 1.924 (0.112-4.302) | 2.442 (0-6.525) |
| | 67 | 113 | 62 | 57 |
| CINE (J kg ⁻¹) | (2-316) | (0-404) | (1-368) | (0-236) |

that over Gr. B stations. During IOP2 it varies between 0-974 m and 112-2512 m for Gr. A and Gr. B stations respectively. This indicates that the dry convection is found to be confined to lower levels over Gr. A stations (LCL < 974 m with high RH) as compared to that over Gr. B stations (112 < LCL < 2512 with low RH). In case of Chennai, where the RH is very low during IOP2, the LCL height reaches up to high levels *i.e.*, 2512 m. During IOP4 the LCL height varies between 0-1114 m for Gr. A stations and 56-1814 m for Gr. B stations. Thus range of variation in LCL heights is more for Gr. B stations during both the IOPs.

The variations of θ and θ_v are shown in [Fig. 3(e) and Fig. 4(e)] during IOP2 and IOP4 respectively for all the stations. Both the parameters show diurnal variation and they follow the same trend. In general, the potential

temperatures are slightly less for Gr. A stations as compared to Gr. B stations. However, θ and θ_v are lower during IOP4 (*i.e.*, August) as compared to those during IOP2 (*i.e.*, July) for Gr. A stations and they are higher for Gr. B stations. During IOP2, θ and θ_v do not show much variation for Gr. A stations whereas for Gr. B stations over Chennai both θ and θ_v are found to be highest with lowest moisture. During IOP4, θ and θ_v follow the same trend as that of IOP2.

From [Fig. 3(f) and Fig. 4(f)] it is seen that in the surface, θ_e is somewhat higher during IOP4 as compared to IOP2 for all the stations except in few cases. The difference in θ_e is clearly seen in case of Gr. B stations. In general, the θ_e is higher for Gr. A stations as compared to Gr. B stations indicating more moist convective activity over Gr. A stations. For Gr. A stations the difference



Figs. 5(a-d). 6-hourly values of CAPE and CINE for the surface air for the stations same as in Figs. 3(a-f) during IOP2 (27-29 July 1999) and IOP4 (12-14 August 1999)

between the θ_{es} values of IOP2 and IOP4 is not seen clearly. However, for the Gr. B stations (particularly MCN and CNN) the θ_{es} values are much higher during IOP2 as compared to IOP4. θ_{es} values are generally low for Gr. A stations as compared to Gr. B stations which are indicative of less dry convection over Gr. A stations. This is also supported by the LCL heights.

The groupwise averaged values of different surface parameters along with their range of variation during IOP2 and IOP4 are given in Table 3. From this table it is seen that the range of variation of all the surface parameters (given in brackets in Table 3) for Gr. A and Gr. B stations indicate high values for Gr. B stations as compared to those of Gr. A stations. Thus the stations which are located very close to the centre of the disturbance are found to be equally affected with little variation whereas the stations situated away from the disturbance show large variations. Also, the variation in different surface parameters for average values of Gr. A

and Gr. B if the same IOP is considered then it is noticed that the range of variation is more for IOP2 as compared to IOP4. In case of IOP2, the observational area is associated with deep depression which differs from low pressure area (during IOP4) in both coverage and intensity. This may be the probable cause of high variation in surface parameters from Gr. A to Gr. B stations during IOP2.

The 6-hourly values of CAPE and CINE during 27-29 July and 12-14 August 1999 for all the coastal stations are shown in Figs. 5(a-d). From this figure it is seen that the CAPE varies from 0 to 5 kJ kg^{-1} [Figs. 5(a&c)] and CINE varies from 0 to 350 J kg^{-1} over all the stations. The values of CAPE are higher during IOP2 as compared to IOP4. This is in corroboration with the prevailing weather conditions and the convective activity. The low values of CINE are associated with large values of CAPE but the reverse is not true. As the duration of both the IOPs is only three days and also the periods are associated

TABLE 4

Extent of different sub layers for Group A (Gr. A) and Group B (Gr. B) stations for 6 hourly averaged profiles during IOP2 (27-29 July 1999)

| Extent of layers | Hours | | | | | | | |
|---------------------|----------|---------|----------|---------|----------|---------|----------|---------|
| | 0000 UTC | | 0600 UTC | | 1200 UTC | | 1800 UTC | |
| | Gr. A | Gr. B | Gr. A | Gr. B | Gr. A | Gr. B | Gr. A | Gr. B |
| Mixed layer | | | | | | | | |
| Extent (hPa) | - | Sur-970 | - | Sur-900 | 990-930 | 990-890 | - | Sur-950 |
| Avg. P^* (hPa) | | -87.8 | | -124.3 | -77.1 | -148.8 | | -94.0 |
| Cloud layer | | | | | | | | |
| Extent (hPa) | 910-750 | 850-700 | 940-670 | 870-760 | 900-640 | 800-680 | 970-590 | 720-650 |
| Avg. P^* (hPa) | -19.8 | -66.4 | -44.9 | -88.7 | -56.8 | -41.0 | -37.1 | -43.8 |
| Depth (hPa) | 160 | 150 | 270 | 90 | 260 | 120 | 380 | 70 |
| Stable layer | | | | | | | | |
| Extent (hPa) | 750-620 | 700-680 | 670-550 | 760-720 | 640-520 | 680-650 | 590-530 | 600-560 |
| Avg. P^* (hPa) | -38.6 | -70.1 | -54.5 | -90.0 | -63.9 | -50.3 | -48.9 | -50.3 |
| CBL top | | | | | | | | |
| Level (hPa) | 620 | 680 | 550 | 720 | 520 | 650 | 530 | 560 |
| P^* (hPa) | -50.3 | -70.6 | -74.2 | -93.5 | -70.0 | -61.5 | -71.4 | -53.3 |
| θ_e (K) | 342.0 | 335.7 | 346.7 | 338.8 | 343.7 | 348.4 | 340.9 | 337.0 |

TABLE 5

Same as Table 4 during the IOP4 (12-14 August 1999)

| Extent of layers | Hours | | | | | | | |
|---------------------|----------|---------|----------|---------|----------|---------|----------|---------|
| | 0000 UTC | | 0600 UTC | | 1200 UTC | | 1800 UTC | |
| | Gr. A | Gr. B | Gr. A | Gr. B | Gr. A | Gr. B | Gr. A | Gr. B |
| Mixed layer | | | | | | | | |
| Extent (hPa) | - | Sur-940 | Sur-910 | Sur-910 | - | Sur-820 | - | - |
| Avg. P^* (hPa) | | -57.3 | -82.8 | -127.2 | | -119.7 | | |
| Cloud layer | | | | | | | | |
| Extent (hPa) | 840-670 | 750-700 | 940-670 | 920-850 | 950-690 | 800-710 | 900-730 | 790-690 |
| Avg. P^* (hPa) | -50.9 | -46.0 | -66.9 | -116.6 | -59.2 | -69.8 | -80.1 | -47.7 |
| Depth (hPa) | 170 | 50 | 270 | 70 | 260 | 110 | 230 | 100 |
| Stable layer | | | | | | | | |
| Extent (hPa) | 670-510 | 700-630 | 670-530 | 740-650 | 650-530 | 710-650 | 620-510 | 690-640 |
| Avg. P^* (hPa) | -53.6 | -54.2 | -65.2 | -83.2 | -59.6 | -73.1 | -71.0 | -55.9 |
| CBL top | | | | | | | | |
| Level (hPa) | 510 | 630 | 530 | 650 | 530 | 650 | 510 | 640 |
| P^* (hPa) | -81.8 | -59.2 | -77.0 | -99.0 | -65.5 | -87.9 | -82.2 | -59.1 |
| θ_e (K) | 336.3 | 333.6 | 341.0 | 334.3 | 338.8 | 335.9 | 337.3 | 335.1 |

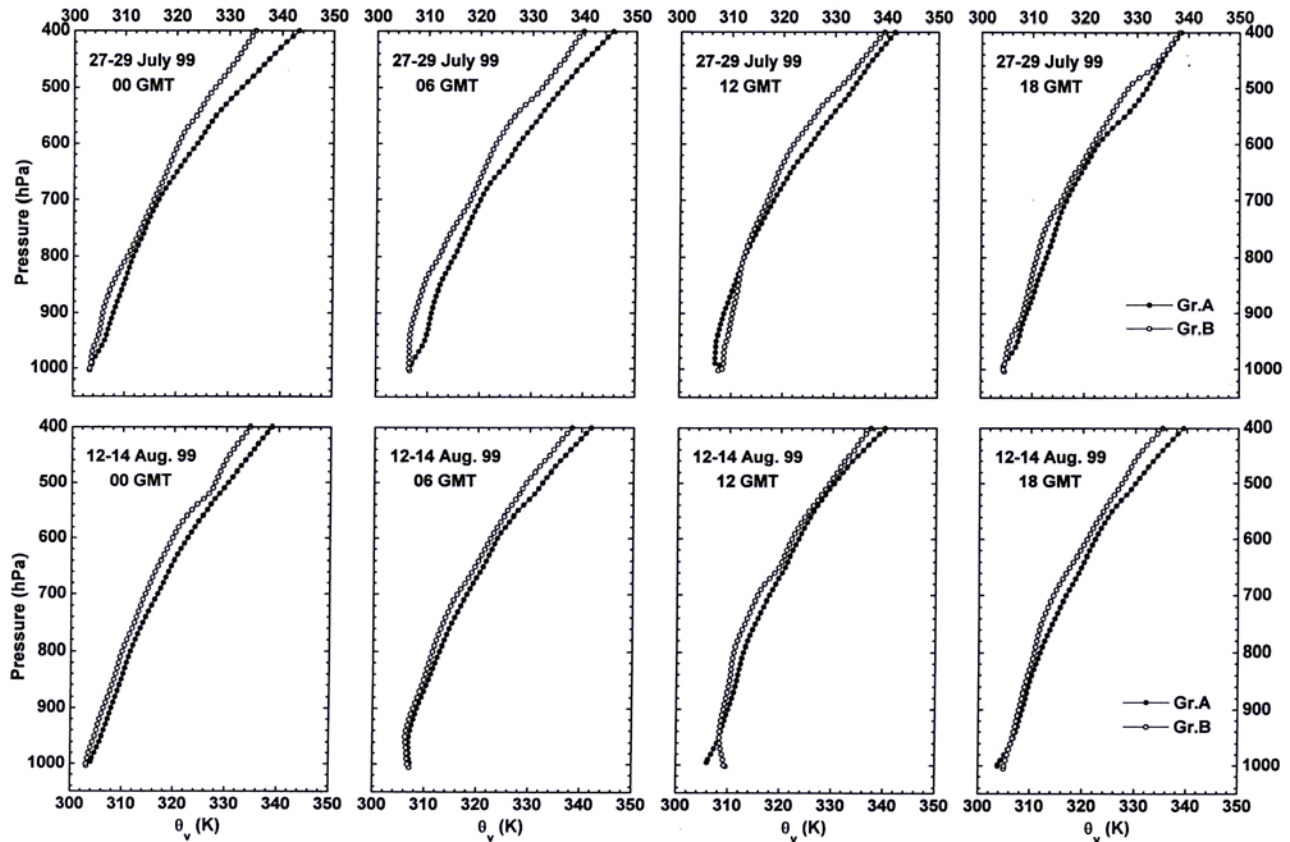


Fig. 6. Vertical distribution of θ_v for the 6-hourly averaged radiosonde soundings for Group A (Gr. A) and Group B (Gr. B) during IOP2 and IOP4

with disturbed weather conditions, it is very difficult to draw any inference about the relation between the CAPE and the changing convective activity as was done by Bhat *et al.* (2001a) over the Bay of Bengal during summer monsoon season and Roy and Bhowmik (2003) for the land stations during the pre-monsoon period. For this purpose a continuous series of data set is required which is not available for east coastal stations as the data was collected only during the IOPs. However, the values of CAPE for all the stations are comparable to those reported by Bhat *et al.* (2001a) over the Bay of Bengal and Roy and Bhowmik (2003) for the land stations (Kolkata and New Delhi). Further, the values of CINE are found to be higher as compared to those obtained over the Bay of Bengal regions (Bhat *et al.* 2001a) and lower as compared to land stations (Roy and Bhowmik, 2003).

From the above discussion it is clearly evident that during July (IOP2) and August (IOP4) the surface parameters appear to show less variation for Gr. A stations. Gr. B stations show higher values of pressure,

temperature, θ , θ_v , θ_{es} , CINE and LCL and lower values of mixing ratio, RH, CAPE and θ_c during July and August. The average values of all the parameters for Gr. A and Gr. B stations (Table 3) is in support of the results obtained from 6-hourly variations of the above surface parameters. During both the IOPs the surface parameters for Gr. A stations are representative of low pressure values, cool and moist air masses, more saturation (high RH), less dry convection (less LCL heights) and more moist convection (high θ_c values). These results are in support of the prevailing weather conditions over these stations.

Vertical profiles of thermodynamic parameters

Temporal and spatial variations

6-hourly averaged vertical profiles (0000, 0600, 1200 and 1800 UTC) of θ_v for Gr. A stations (solid line with solid circle) and Gr. B stations (solid line with open circle) during IOP2 (July) and IOP4 (August) are shown in Fig. 6. Also, the extent of the different sub layers *i.e.*,

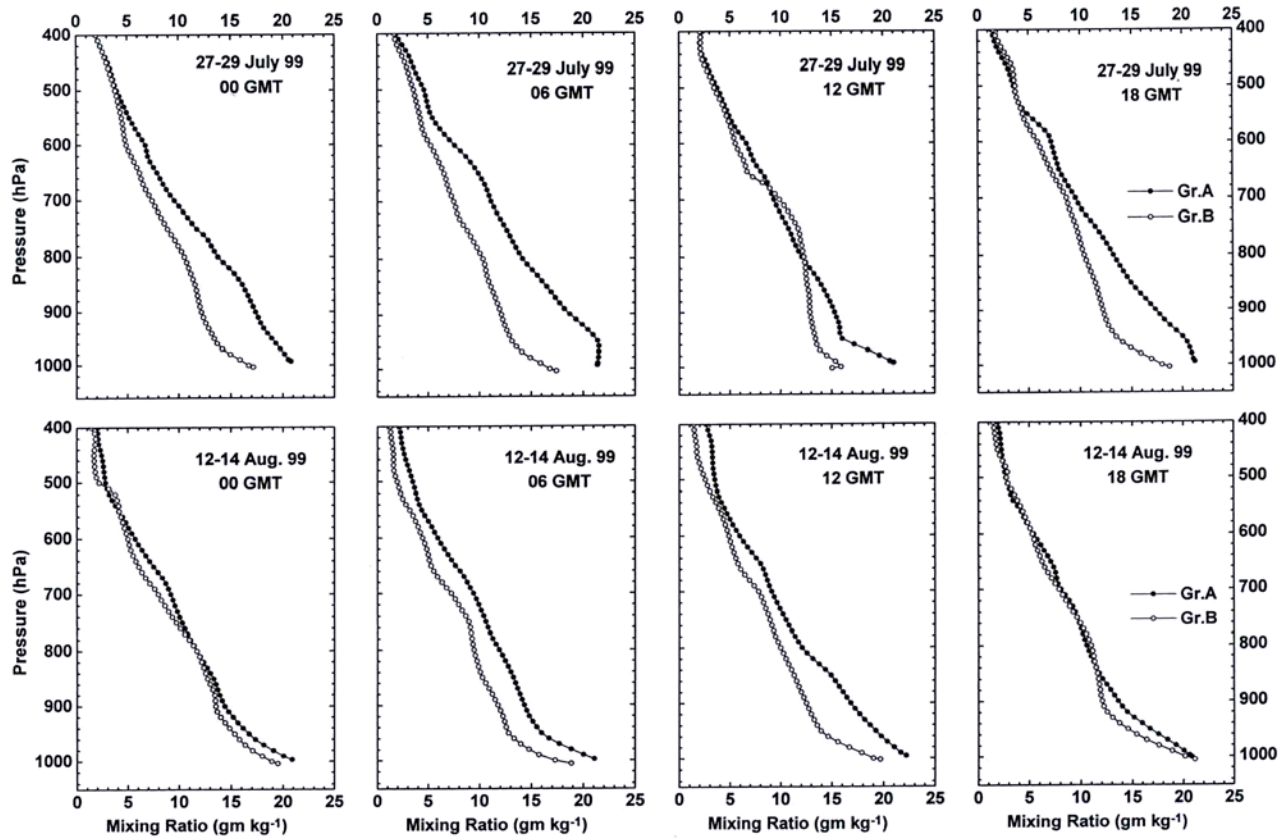


Fig. 7. Same as Fig. 5 for mixing ratio (q)

mixed layer (or sub cloud layer), cloud layer and the overlying stable layer at 0000, 0600, 1200 and 1800 UTC hours for Gr. A and Gr. B stations during the periods in July (IOP2) and August (IOP4) are given in Tables 4 and 5 respectively. The level up to which CBL extends (*i.e.*, CBL top) and the average values of P^* in each layer are also tabulated in these tables.

From Fig. 6 it is seen that during both the periods θ_v shows gradual increasing trend from surface up to 400 hPa with change in slope at different levels (Parasnis and Morwal, 1991) indicating the presence of different sub layers of different characteristics. In general, the θ_v is higher during day time hours (0600 and 1200 UTC) as compared to night time hours (0000 and 1800 UTC) during both the IOPs. At 0000 and 0600 UTC θ_v is more for Gr. A stations than Gr. B stations at all levels from surface up to 400 hPa during both July and August periods. This difference appears to be more above 650 hPa level. This indicates more stable conditions over Gr. A stations. As Gr. A stations are located in the vicinity of the centre of disturbance, the atmosphere shows more stability

at all levels over Gr. A stations. Parasnis (1991) reported high stability during active monsoon conditions over an inland station, Pune while comparing the CBL characteristics during active and break monsoon conditions. Thus, the conditions over Gr. A stations are indicative of active monsoon conditions. For 1200 and 1800 UTC hours the difference in θ_v profiles for Gr. A and Gr. B stations is less during IOP2 and IOP4 both as compared to that for 0000 and 0600 UTC. Also, at 1200 UTC the θ_v values in the lower layer are cooler for Gr. A stations as compared to Gr. B stations. This is in support of the results obtained in case of surface θ_v and θ_e values over Gr. A stations. The difference in the vertical profiles of θ_v for Gr. A and Gr. B stations is more during IOP2 as compared to that of IOP4.

The layer adjacent to the earth's surface which is associated with nearly constant values of θ_v (lapse rate less than 2 K km^{-1}) is termed as mixed layer (ML). ML is situated just above the surface layer and continuously interacts with the underlying surface layer. The energy from the surface is first received by ML and then

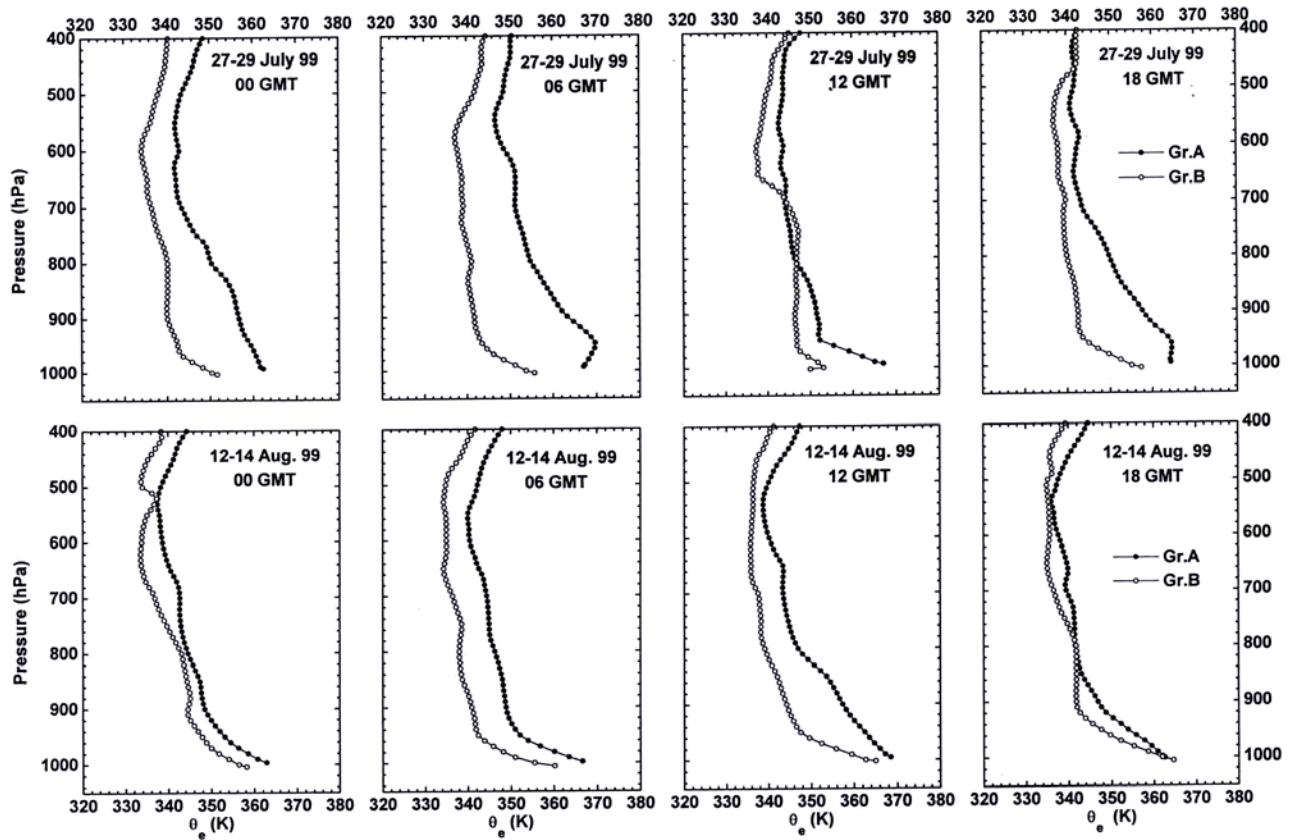


Fig. 8. Same as Fig. 5 for Equivalent potential temperature (θ_e)

transported upwards by clouds (Bhat *et al.*, 2001b). Also, according to Malkus (1956) the mixed layers are generally associated with the well mixed layers in potential temperature and constant or slight decrease of mixing ratio. In the present case the ML is observed only on few occasions for Gr. A stations at 1200 UTC (IOP2) and 0600 UTC (IOP4) extending up to 930 and 910 hPa respectively, indicating that the moist convection dominates in case of Gr. A stations during both the IOPs. The extent of the ML varies between 910-820 hPa for Gr. B stations at 0600 and 1200 UTC and MLs are shallow at 0000 and 1800 UTC (up to 940 hPa). Thus for Gr. B stations evolution of the MLs (*i.e.*, extent of the dry convection) is clearly evident from morning (940 hPa) to evening (820 hPa) hours during both the IOPs. This is in support of the results obtained by Parasnis *et al.* (1991) utilizing the SODAR data collected during MONTBLEX-1990 over Kharagpur. From Tables 4 and 5 it is seen that the magnitude of average P^* values (which are indicative of the lack of saturation in the ML) are more at 0600 and 1200 UTC ($-149 < P^* < -119$ hPa) as compared to 0000

and 1800 UTC ($-94 < P^* < -57$ hPa) during both IOP2 and IOP4. This indicates that the MLs are comparatively dry during day time hours (0600 and 1200 UTC) as compared to those during morning (0000 UTC) and night (1800 UTC).

Fig. 7 shows the groupwise 6-hourly averaged vertical profiles of mixing ratio during IOP2 and IOP4. All the mixing ratio profiles show a monotonic decreasing trend from surface up to 400 hPa level with a slight change in the slope at different levels. The same structure of mixing ratio is observed over Pune, an inland station (Parasnis and Morwal, 1991) and over Bay of Bengal oceanic region (Morwal, 2002). The mixing ratio for Gr. A stations is more as compared to Gr. B stations for all the profiles from surface up to 400 hPa. This may possibly be due to the fact that the Gr. A stations are located near the region of disturbance and hence more moisture is transported up to higher levels due to the presence of low level convergence which is not present for the stations located further away from the disturbance *i.e.*,

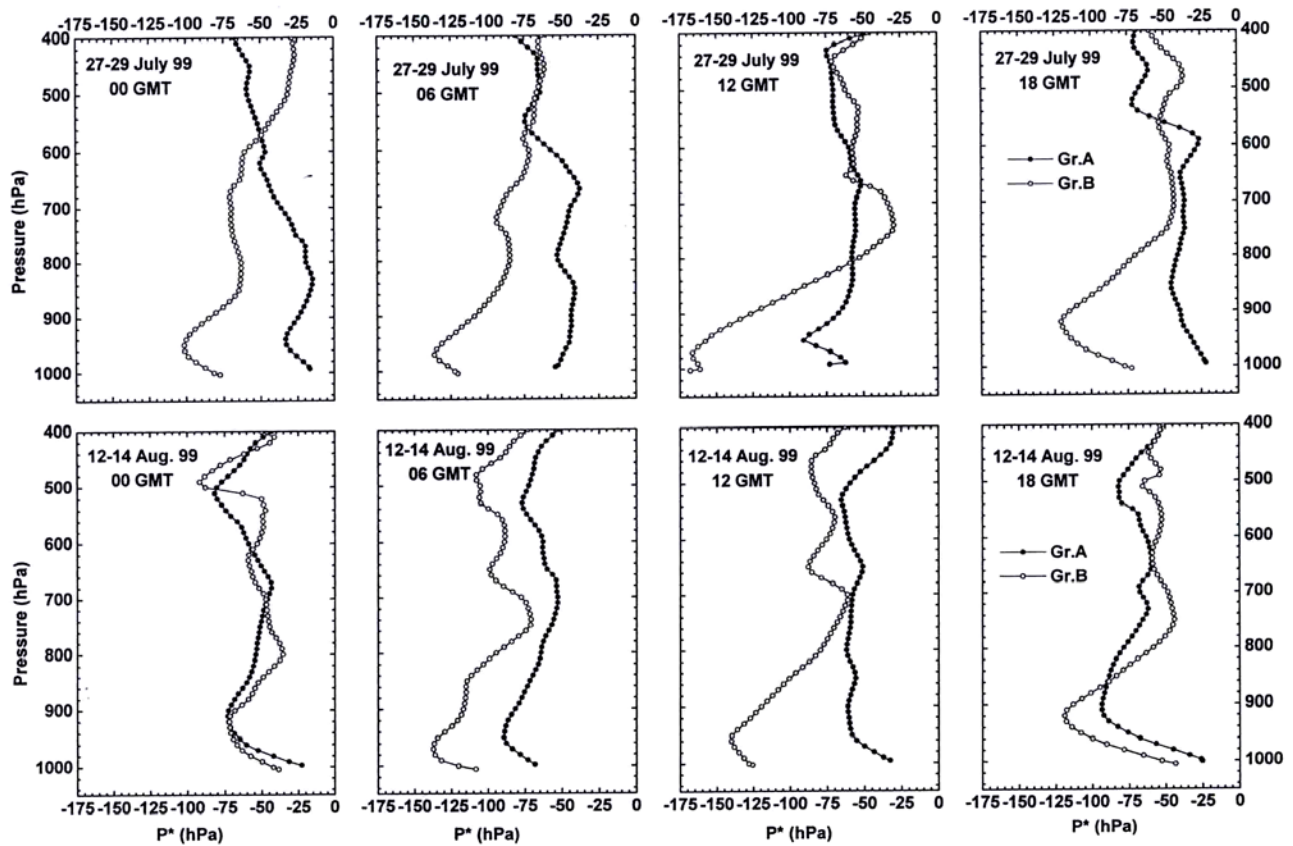


Fig. 9. Same as Fig. 5 for saturation pressure deficit (P^*)

Gr. B stations. Similar type of CBL structure is reported by Parasnis (1991) while studying the CBL structure during active and break monsoon conditions over Pune region. Parasnis (1991) reported high values of q during active monsoon conditions as compared to break monsoon conditions. This difference between mixing ratio values of Gr. A and Gr. B stations is more in the lower layers (up to 850 hPa) and negligible in the higher layers (above 550 hPa). Maximum difference in q is observed around 950 hPa. Further, it is noticed that in the lower layers q is more for both the groups during IOP4 as compared to IOP2.

The 6-hourly averaged vertical profiles of θ_c for Gr. A and Gr. B stations during IOP2 and IOP4 are shown in Fig. 8. θ_c is representative of the observed moist convection over the region and is influenced by both *i.e.*, changes in temperature and mixing ratio. It is clearly evident from all the θ_c profiles that the lower layers (< 900 hPa) show more convective instability and they become nearly neutrally stratified above that. For Gr. A stations the convective instability in the lower layers is

comparatively less than that of Gr. B stations. Similar results were reported by Parasnis (1991) and Parasnis *et al.* (1991) over the different land stations during the summer monsoon season. In general, θ_c values are more for Gr. A stations as compared to that of Gr. B stations at all levels, indicating more moist convection over Gr. A stations. The difference in θ_c for Gr. A and Gr. B stations is more in the lower layers (below 800 hPa) as compared to layers above. The comparison of θ_c profiles during IOP2 and IOP4 indicate that the moist convection is more during IOP2 (higher θ_c) for both the Groups. During IOP2 the θ_c in the surface layer for different synoptic hours for Gr. B and Gr. A stations varies from 350 - 358 K and 362 - 370 K respectively. Also, in case of Gr. A stations the θ_c values are more than 340 K and for Gr. B stations this lower limit of θ_c is 334 K. For Gr. B stations the θ_c is more for 0600 and 1200 UTC as compared to 0000 and 1800 UTC at all levels indicating more convective activity during the day time hours as compared to morning and night hours (*i.e.*, diurnal variation). Similar features are observed during IOP4. However, the magnitude of moist convection during IOP4 is less for both Gr. A as well as Gr. B stations as compared to respective groups of IOP2.

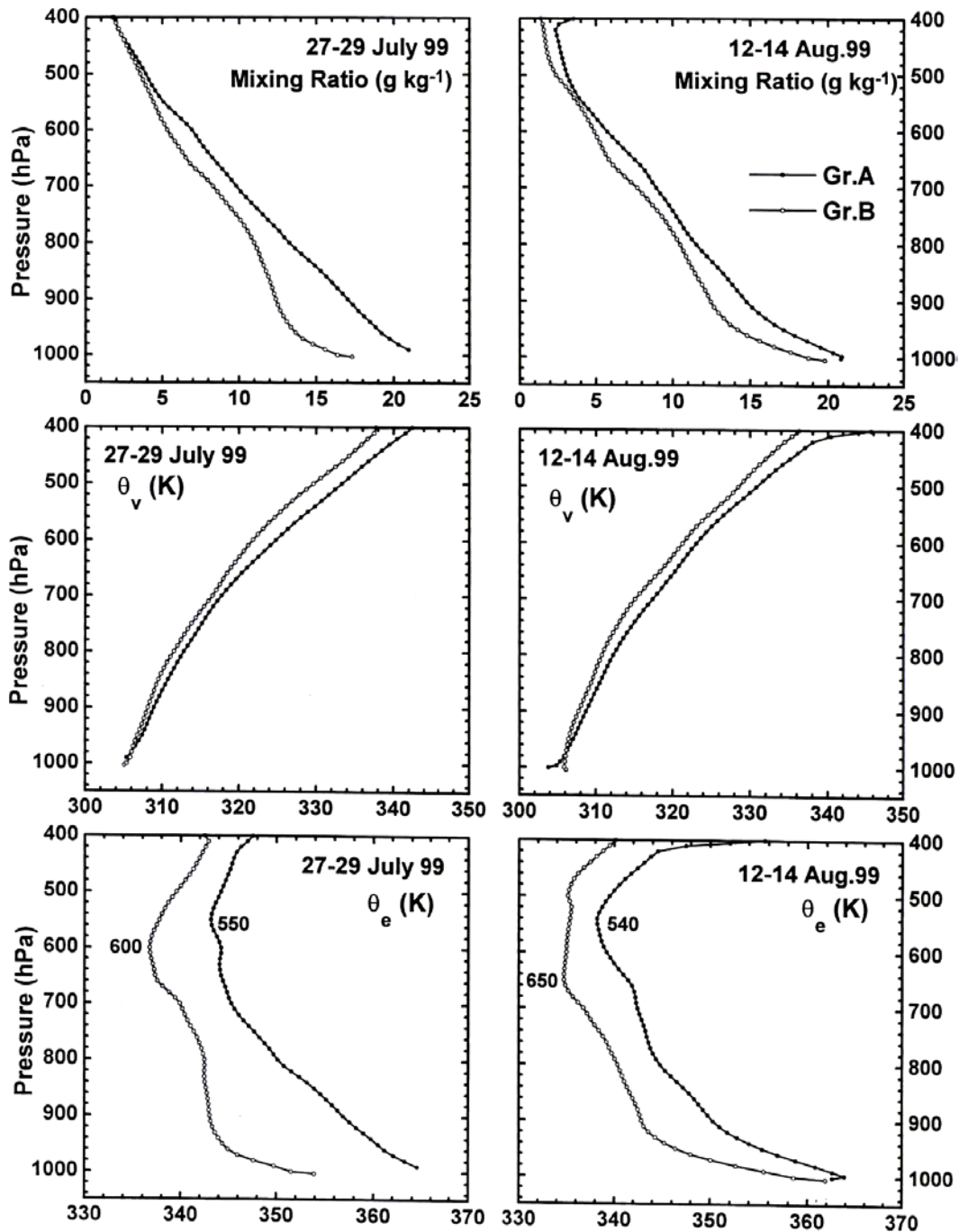


Fig. 10. Vertical distribution of mixing ratio, θ_v and θ_e for the averaged radiosonde soundings during IOP2 and IOP4 for Group A (Gr. A) and Group B (Gr. B) stations

Betts and Albrecht (1987) determined the CBL top by utilizing the vertical profiles of θ_e , θ_{es} and P^* . They found that the CBL top coincides with the level of θ_e and P^* minimum and θ_{es} maximum. In the present study the θ_e minimum and θ_{es} maximum are not so pronounced as observed by Betts and Albrecht (1987) over the Pacific

oceanic regions because the sounding considered by them were associated with the low level inversions. Here, in none of the soundings inversion/isothermal layers are observed and the region is dominated by deep moist convection. Hence, at the CBL top flat minimum values of θ_e are found. Tables 4 and 5 show the values of CBL top

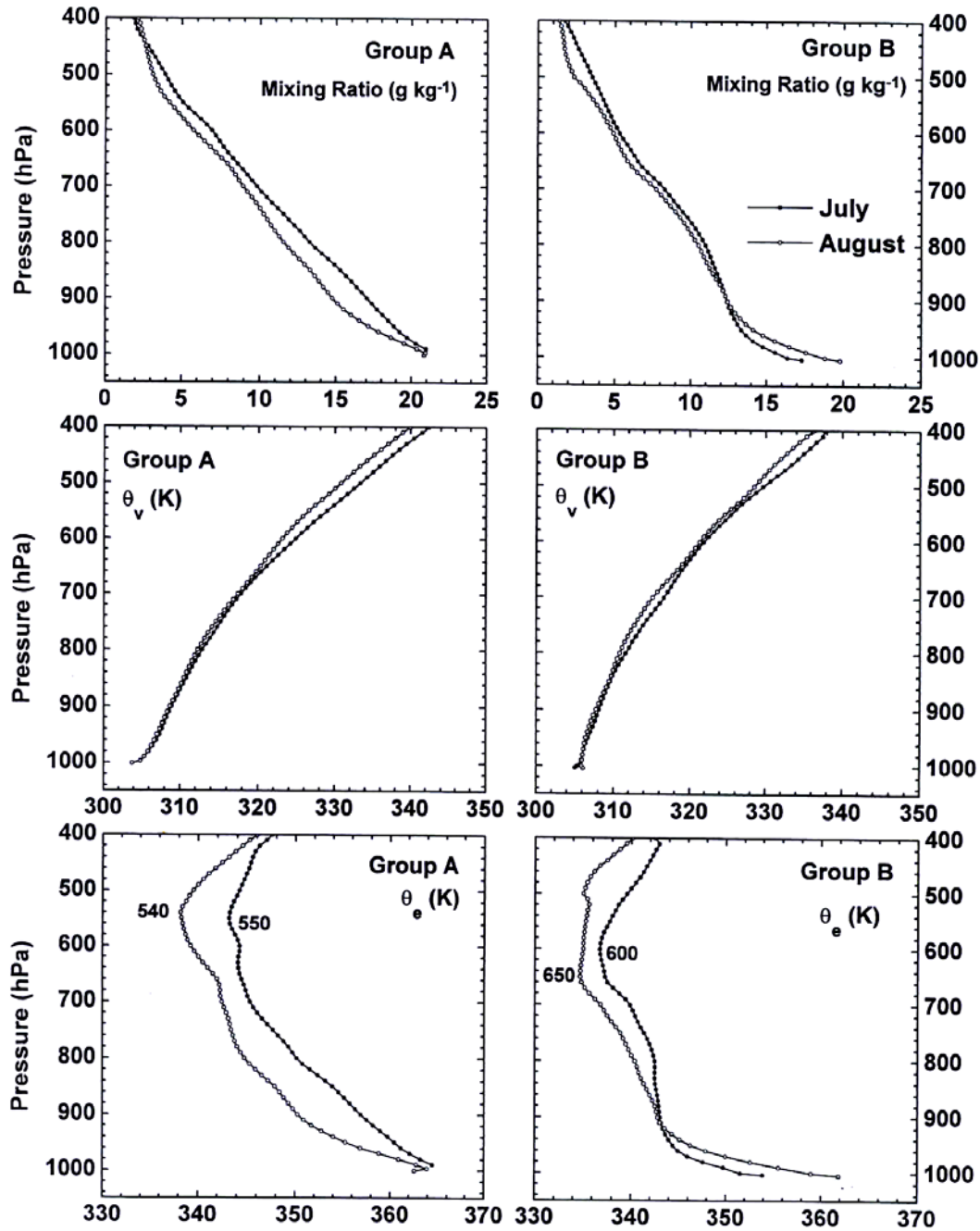
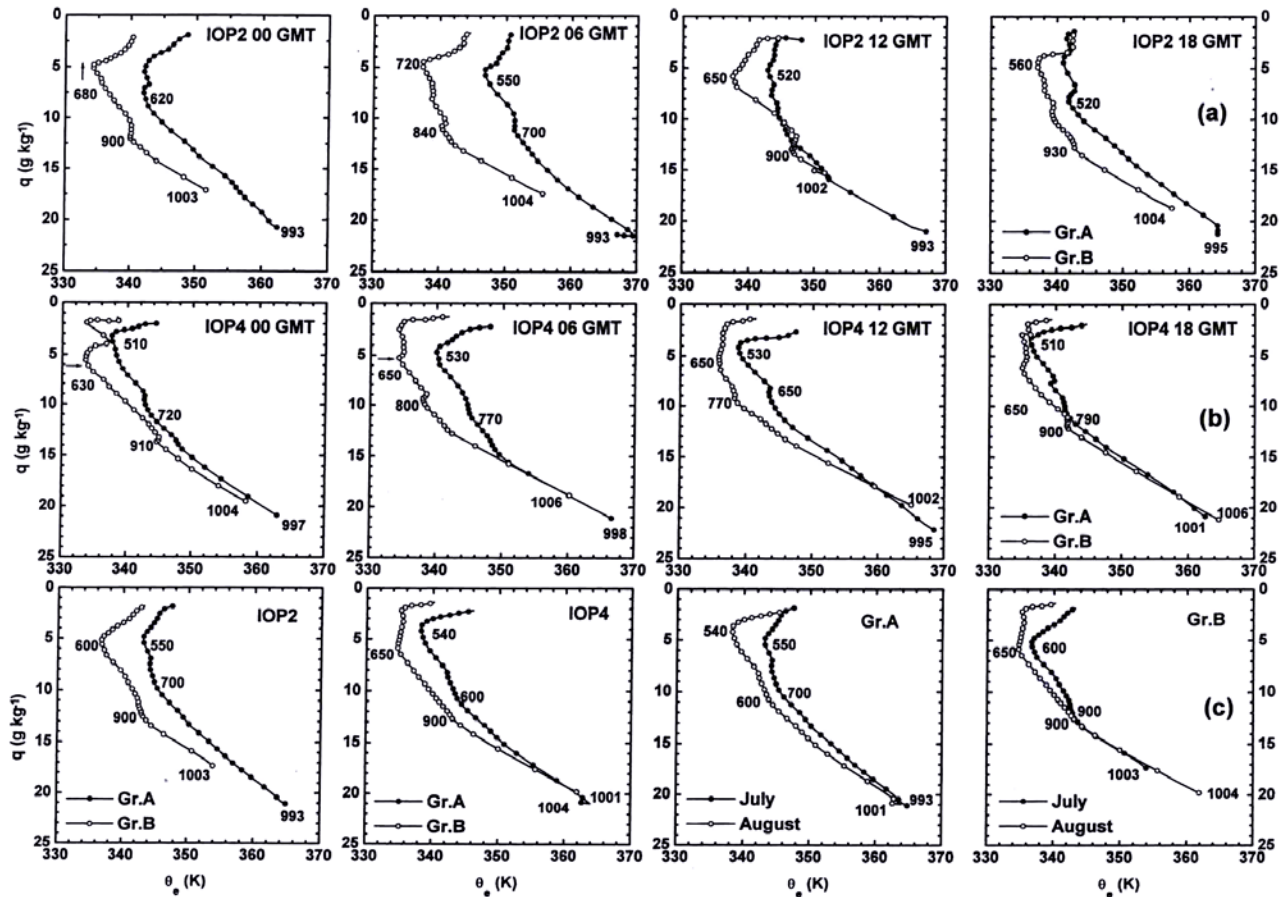


Fig. 11. Vertical distribution of mixing ratio, θ_v and θ_e for the averaged radiosonde soundings for Group A (Gr. A) and Group B (Gr. B) stations during July and August

at 0000, 0600, 1200 and 1800 UTC for Gr. A and Gr. B stations during IOP2 and IOP4 respectively. From these tables it is observed that the CBL top lies in the range 720-510 hPa. Also, the CBL top for Gr. B stations is at lower levels as compared to Gr. A stations for all the synoptic hours. This indicates that the moist convection

reaches up to higher levels over the stations (Gr. A) which are situated in the vicinity of the disturbance. These results are in support of those reported by Parasnis and Morwal (1991) and Parasnis (1991) over an inland station, Pune during the summer monsoon seasons of 1980 and 1981. They have reported the CBL top varying in the



Figs. 12(a-c). Conserved variable diagrams (a) During IOP2 over Gr. A and Gr. B stations (b) During IOP4 over Gr. A and Gr. B stations (c) Average plots during IOP2, IOP4 for Gr. A and Gr. B stations and average plots for Gr. A and Gr. B stations during July and August

range 700-600 hPa. By comparing the results obtained by them with our results, it is evident that the extent of the CBL for the coastal stations (720-510 hPa) is more than that observed over an inland station, Pune (700-600 hPa).

P^* i.e., saturation pressure deficit is computed at each level utilizing the formula $P^* = p_{SL} - p$. Where p_{SL} indicates the pressure at saturation level (i.e., LCL level) for the parcel at pressure p . P^* is considered as an indicator of lack of saturation in the layer p to p_{SL} . The unsaturated region is associated with the negative values of P^* and in the cloudy region P^* is positive. Thus as the air becomes less saturated the P^* attains high negative values. In the sub cloud layer the P^* increases and it attains nearly constant value in the cloud layer. The stable layer is associated with decreasing trend of P^* . Here vertical profiles of P^* (Fig. 9) indicate that during July (i.e., IOP2) the layers below 600 hPa are more saturated (less negative values of P^*) at all UTC hours for Gr. A

stations except at 1200 UTC. During July (IOP2) the cloud layer depths (Table 4) for Gr. A stations at 0000, 0600, 1200 and 1800 UTC are 160, 270, 260 and 380 hPa respectively which are more in comparison to 150, 90, 120 and 70 hPa for the respective UTC hours for Gr. B stations. This indicates that the moist convection is more over the Gr. A stations as compared to that over Gr. B stations. Also, at 1200 UTC the cloud layer even though shallow is more saturated for Gr. B stations as seen from Fig. 9. During IOP4, the atmosphere is more saturated at all levels for Gr. A stations as compared to Gr. B stations for 0600 and 1200 UTC whereas the conditions are more or less similar at 0000 and 1800 UTC. Also, the depth of the cloud layer (Table 5) at all the four 6-hourly observations is more over Gr. A stations (170, 270, 260 and 230 hPa) as compared to that of Gr. B stations (50, 70, 110 and 100 hPa). These results are similar to those reported in Morwal (2002) over the Bay of Bengal region utilizing the observations collected during the passage of disturbance for the four ships positioned stationary in a polygon during 11-18 August 1977.

As mentioned above the CBL height is determined by using the vertical profiles of P^* and it is found to be coinciding with minimum values of P^* and θ_e . The CBL heights are listed in Tables 4 and 5 for both the groups at standard UTC hours during the periods in July (IOP2) and August (IOP4) respectively. During July the CBL tops for Gr. A and Gr. B stations vary from 620-520 hPa and 720-560 hPa respectively. These values during IOP4 are 530-510 and 650-630 hPa respectively. This indicates that the CBL tops do not vary much during IOP4 for both the groups during different synoptic hours. However, the variation is more during IOP2 indicating the influence of the prevailing synoptic scale weather system (deep depression). The CBL tops reach up to higher levels for the Gr. A stations (520 hPa) as compared to Gr. B stations (560 hPa). The prevailing weather system during IOP4 is weak as compared to that during IOP2.

From the above discussion it is clear that during August period the atmosphere, in general, is less saturated at all levels except at the surface as compared to July period. For Gr. A stations, the vertical structure of the CBL during August is more or less similar to that in July except few marked differences. During August period there is less variation in P^* values for Gr. A and Gr. B stations as compared to July profiles except at 1200 UTC. During August above 900 hPa the CBL is more saturated for Gr. B stations at 0000 and 1800 UTC whereas at 0600 and 1200 UTC Gr. A stations show more saturation (low values of P^*). The variation in CBL top is very less during August period for both the groups (Gr. A 530-510 hPa and Gr. B 650-630 hPa) as compared to July period (Gr. A : 620-520 hPa and Gr. B : 720-560 hPa).

Average vertical profiles in the CBL

Further, in order to explore the differences in the CBL structure during July and August periods groupwise averaged values of T and T_d have been computed for the IOP2 and IOP4 from surface up to 400 hPa at an interval of 10 hPa. These averaged vertical profiles have been used to compute the different thermodynamic parameters. The results of the investigation are presented in the following discussion.

Fig. 10 shows the averaged vertical profiles of mixing ratio, virtual potential temperature (θ_v) and θ_e for Gr. A and Gr. B stations during IOP2 (27-29 July 1999) and IOP4 (12-14 August 1999). From this figure it is seen that Gr. A stations are associated with high values of mixing ratio, θ_v (except in the lower layers adjacent to the earth surface) and θ_e at all levels during both the periods in July and August. This indicates that the stations which are located in the vicinity of the disturbance (*i.e.*, Gr. A stations) are influenced more as compared to the stations

situated away (*i.e.*, Gr. B stations) from the disturbance. Thus, the CBLs for Gr. A stations are representative of more warm, moist and deep moist convective activity as compared to Gr. B stations. The CBL tops for Gr. A and Gr. B stations are at 550, 600 hPa and 540, 650 hPa (marked in Fig. 10 at minimum value of θ_e) respectively for IOP2 and IOP4. This indicates that moist convection reaches up to higher levels (550-540 hPa) over Gr. A stations as compared to that over Gr. B stations (650-600 hPa).

Fig. 11 shows the averaged vertical profiles of mixing ratio, θ_v and θ_e during July (solid line with solid circles) and August (solid line with open circles) periods for Gr. A and Gr. B stations. This figure is very useful to compare the CBL structure during the two IOPs. The mixing ratio profiles indicate that for Gr. A stations, the mixing ratio is high during July (variation is from 0 to 2.3 gm kg⁻¹) at all levels. These variations are negligible for Gr. B stations, except in the layers below 900 hPa and above 550 hPa. This confirms that the stations which are located away from the prevailing weather system show very little influence of the prevailing system on the vertical structure of the CBL. The θ_v profiles during July and August for both the groups follow the same trend, and difference is negligible up to 700 hPa. The θ_e profiles for Gr. A stations indicate that at the surface moist convective activity is more or less same during July and August. However, in the vertical layers convective activity is more during July as compared to August period. This indicates that the system which prevailed during July have more influence on the nearby stations as compared to August. For Gr. A stations the CBL top reaches more or less up to same level (~550 hPa) during both the periods. Thus the CBL top remains more or less unchanged for the active monsoon conditions during the summer monsoon season. For Gr. B stations the moist convective activity during August is more up to 900 hPa level and *vice versa* above that. Also, the CBL top is observed at higher level (600 hPa) during July as compared to August (650 hPa). Thus for the stations away from the location of the disturbance the moist convection is reaching up to higher levels during July indicating some influence even over the stations situated far away. This may be due to the difference in the nature of the prevailing synoptic scale disturbance and its intensity *i.e.*, deep depression during July period and a low pressure area during August period.

Conserved-variable diagrams

The conserved variable diagram *i.e.*, θ_e - q_T diagram is commonly used to understand the mixing processes in the atmosphere. The ordinate is usually q_T , the total water content, while θ_e is the abscissa. In the present study ordinate is considered as q , mixing ratio, as the

atmosphere considered in the present study is unsaturated. Also, the ordinate is reversed so that it resembles the vertical distribution of mixing ratio in atmosphere. In conserved variable diagrams both the axes are linear. Thus, if these variables mix linearly, then the mixing occurs along straight lines on these diagrams (Emanuel, 1994). Therefore, mixing lines are straight lines on these diagrams. In these diagrams, both the axes are conserved thermodynamic variables and the pressure (or position) of a parcel is indicated at different levels. The position of a parcel does not change under reversible adiabatic processes but under the influence of some irreversible or diabatic processes, such as fallout of precipitation or radiation, the position of a parcel can change. Fallout or evaporation of precipitation is indicated by a nearly vertical displacement to smaller or large values of q along a constant θ_e line. Radiative heating or cooling displaces the air parcel laterally to higher or lower θ_e along a constant q line.

θ_e - q diagrams for 6-hourly UTC hours for Gr. A and Gr. B stations during IOP2 and IOP4 are shown in Fig. 12(a) & Fig. 12(b) respectively. Further, θ_e - q plots for averages for IOP2 and IOP4 over Gr. A and Gr. B stations and also for Gr. A and Gr. B stations during July and August are shown in Fig. 12(c). In each θ_e - q diagram the pressure is denoted at the surface, CBL top and some significant levels. The mixing lines for Gr. A and Gr. B stations during IOP2 and IOP4 indicate that the CBLs are moister and warmer at all hours from surface up to CBL top for Gr. A stations as compared to Gr. B stations. Also the moist convective activity is more over Gr. A stations in comparison to that over Gr. B stations. All the mixing lines are straight lines in the CBL and show a change in slope (in θ_e) at the CBL top. The CBL top is associated with the minimum value of θ_e . Thus the CBL during both the IOPs for Gr. A and Gr. B stations is characterized by a single mixing line structure. However, the mixing lines in most of the cases show a slight change in slope of the mixing line (the pressure at these levels is indicated in all the plots in Fig. 12). At these levels the θ_e is either nearly constant or increases slightly. These levels are mostly observed above the mixed layers and below the cloud layers. This may possibly be due to the release of heat during the process of condensation of the water vapour at the cloud base level. However, Betts and Albrecht (1987) have observed double mixing lines over the areas of deep moist convection over the Pacific oceanic regions which is not observed in the present study in spite of all the stations are located in the deep moist convective zone. This shows that the CBL structure is controlled by the prevailing synoptic scale weather system and the convective mixing dominates over the processes that do not conserve the position of the air parcel such as radiative cooling or the processes of precipitation and evaporation of falling rain.

The CBL top is marked by minimum of θ_e which is associated with the change in the slope of the mixing line. It is noticed that the CBL top is not associated with the minimum value of q or reversals in θ_e and q gradients with height as observed by Betts and Albrecht (1987). In the present study the observational area falls in the ascending deep moist convective zone as described by Sikka and Narasimha (1997). This may be the plausible reason for the absence of the double mixing line structure. Thus, from these investigations it is clearly evident that the CBLs over the east coastal stations under the influence of synoptic scale weather system are representative of single mixing line structure and are dominated by the vertical thermodynamic mixing processes. These results are tentative and needs to be confirmed by utilizing the dataset available for other IOPs.

5. Summary of the results

A study has been carried out utilizing the special high resolution aerological observations collected over the six Indian east coastal stations during two Intensive Observation Periods (IOPs) falling in July (IOP2, 27-29 July, 1999) and August (IOP4, 12-14 August, 1999) of the summer monsoon of 1999 as part of BOBMEX-99. During both the periods a synoptic scale weather system was observed over the inland stations northwest of Bhubaneswar. These systems were varying in its intensity *viz.*, deep depression (IOP2) and low pressure area (IOP4). The east coastal stations are classified into two groups based on surface pressure distribution and also on the basis of the position of the stations with respect to the prevailing synoptic scale disturbance in the Bay of Bengal region. The two groups thus formed are: (i) Gr. A stations which include the stations Kolkata (KOL), Bhubaneswar (BWN) and Vishakhapatnam (VSK) and are characterized by low values of surface pressure and are situated in the vicinity of the disturbance and (ii) Gr. B stations including the stations Machilipatnam (MCN), Chennai (CNN) and Karaikal (KKL) which are associated with relatively high values of surface pressure and located far away from the centre of disturbance. An attempt has been made to explore the CBL structure over the east coastal stations and also to carry out the comparative investigations between the two Groups of stations with respect to prevailing synoptic scale weather systems. The results of the study are summarized below.

Daily march of surface parameters *viz.*, pressure, temperature, mixing ratio, relative humidity, height of the lifting condensation level (LCL), θ , θ_s , θ_e , and θ_{es} for all the stations during July and August periods indicated:

(i) The Gr. A stations (KOL, BWN and VSK) showed lower values of pressure, temperature, LCL heights, θ , θ_s ,

and θ_{es} and higher values of mixing ratio, RH and θ_e indicating existence of cool, moist and saturated CBLs over Gr. A stations.

(ii) Gr. B stations are associated with higher values of pressure, temperature, θ , θ_v , θ_{es} and LCL heights and lower values of mixing ratio, relative humidity and θ_e during July and August. This indicates that the CBLs over Gr. B stations are comparatively warm, dry and less saturated.

(iii) The range of variation (given in the bracket in Table 3) in all the surface parameters, described here, is less for Gr. A stations as compared to Gr. B stations.

(iv) The range of variation in the surface parameters between Gr. A and Gr. B stations is more during IOP2 as compared to IOP4. Thus the influence of the prevailing synoptic scale weather system on the surface parameters is varying from Gr. A to Gr. B stations. These results are in support of the investigations carried out by Morwal (2002) to examine the variations in the surface parameters with respect to the synoptic scale system over the Bay of Bengal region utilizing the observations collected onboard four ships positioned stationary.

The investigation of the 6-hourly averaged vertical profiles of different thermodynamical parameters *viz.*, θ_v , q , θ_e and P^* for Gr. A and Gr. B stations during July and August periods explored that:

(v) Gr. A stations showed high values of q , θ_v and θ_e at all levels for all 6-hourly averaged vertical profiles indicating warm and moist CBLs and the region is dominated by deep moist convection. Thus the stations which are in the vicinity of the synoptic scale disturbance show more influence of the disturbance as compared to the stations away from it. These results are corroborated by the results obtained by Parasnis (1991); Morwal (2002) and Parasnis *et al.* (1991). Parasnis (1991) reported similar type of variations in the vertical structure of the CBL during the contrasting monsoon conditions. In order to examine the influence of the monsoon trough on the CBL structure Parasnis *et al.* (1991) investigated the CBL structure over the stations located north and south of the monsoon trough. They reported that the stations located to the south of the monsoon trough are dominated by the deep moist convection and the stations located north of the monsoon trough showed suppressed convection.

(vi) The difference in the mixing ratio values is more during day time (0600 and 1200 UTC) in comparison to night time hours (0000 and 1800 UTC) for both the groups.

(vii) From the vertical profiles of θ_e it is noticed that moist convective activity is slightly more during day time as compared to night time.

(viii) The values of CAPE lies in the range 1-4 kJ kg⁻¹ over all the east coastal stations and it is comparable to the values obtained over the Bay of Bengal region (Bhat *et al.*, 2001a) and over the land stations (Roy and Bhowmik, 2003). Also, the values of CAPE are found to be more for IOP4 as compared to IOP2. The variation in the values of CINE is from 0 to 350 J kg⁻¹. The values of CINE are found to be higher as compared to those over Bay of Bengal region and lower as compared to land regions.

(ix) The vertical profiles of P^* is used to delineate the different sub layers in the CBL. The cloud layer is associated with nearly constant values of P^* . Thus, the extent of the cloud layers are found to be more for Gr. A stations as compared to those of Gr. B stations for all synoptic hours during both July and August periods. As the conditions over Gr. A stations are representative of active monsoon conditions, these results are in support of the results reported in Parasnis (1991); Morwal (2002) and Morwal and Seetaramayya (2003). This indicates that the Gr. A stations are associated with more moist convective activity as compared to that over Gr. B stations.

(x) The CBL top is found to be associated with the minimum values of θ_e (flat minimum) and P^* . The CBL top for Gr. A stations (550, 540 hPa) is found to be at higher levels as compared to Gr. B stations (600, 650 hPa) during July and August indicating moist convection reaching up to higher levels for Gr. A stations due to the presence of the synoptic scale disturbances which is responsible for pumping of the heat and moisture from the surface layer to the layers aloft. In case of inland station, Pune, Parasnis and Morwal (1991) reported the extent of the CBL from 700-600 hPa whereas it is noticed from the present study that under the influence of the synoptic scale weather disturbance the CBL extends up to higher levels (650-540 hPa) over the coastal stations.

(xi) The conserved variable diagrams (θ_e - q) are used to understand the mixing processes in the CBL and also to understand the influence of the irreversible physical processes *viz.*, radiation, precipitation or evaporation of the precipitation etc. on the modification of the mixing line. These diagrams showed presence of single mixing line structure over both the groups during IOP2 and IOP4. Further, the CBL tops obtained by utilizing the θ_e - q diagrams are found to be similar to those determined using the vertical profiles of thermodynamic parameters. These results are tentative and needs confirmation by considering the data collected during the remaining IOPs

and also the whole available dataset during BOBMEX-99 for the east coastal stations.

Average vertical profiles of q , θ_v and θ_e during July and August indicate more variation for Gr. A stations as compared Gr. B stations (Fig. 11). However, the values of q , θ_v and θ_e are more during July (except in the surface layer) at all levels from surface up to 400 hPa indicating more moist convection during July than August period. These variations are negligible for Gr. B stations. The θ_v profiles are more or less same up to 650 hPa. However, the q profiles indicate more variability below 650 hPa. This indicates that during the summer monsoon season the moist convection plays a major role in the atmospheric processes.

Acknowledgements

The author is thankful to Dr. G. B. Pant, Director, IITM, Pune for the facilities provided for carrying out this work. The author is also thankful to Dr. P. C. S. Devara, DD (Head PM&A) for continuous support and encouragement. Author is grateful to Dr. P. E. Raj for fruitful discussion and suggestions during the preparation of the manuscript and also for careful examination of the manuscript. The radiosonde data for land stations used in this report is made available by India Meteorological Department; the author gratefully acknowledges the data source. Thanks are also due to the Department of Science and Technology, Government of India for sanction and granting the financial support for the execution of the project (ES/48/ICRP/10/99). The author is also thankful to the anonymous referee for the fruitful suggests and comments which proved of immense use while modifying the manuscript of the paper.

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