J. Ind. Geophys. Union (July 2005)
Vol.9, No.3, pp.219-233

Thermodynamic characteristics over North Bay of Bengal during active and weak monsoon phases of BOBMEX-1999

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ABSTRACT

The Bay of Bengal Monsoon Experiment (BOBMEX-99) was carried out during peak monsoon months of July and August, 1999. The surface and the upper air Radiosonde data acquired onboard Ocean Research Vessel (ORV) Sagarkanya, at the stationary position 17.5°N, 89.0°E, during this experiment have been analysed for the periods 28 July to 5 August (Phase I) and 14 to 22 August (Phase II). The analysis of the various parameters over Indian region has shown intra-seasonal fluctuations of active and weak monsoon episodes during these two phases respectively. In addition, day to day variations in the vertical profiles of RH, θe, θes and P in the midtroposphere, at the stationary position of the ship, are observed to be more significant during Phase I than Phase II. The atmosphere near the surface over north Bay of Bengal seems to be conducive to the formation of convection during both the phases. However, over the north bay, three intense synoptic scale disturbances are formed during Phase I while, only a single upper air cyclonic circulation was developed during Phase II.

INTRODUCTION

Generally, during July and August a semi-permanent zone of low pressure, called as monsoon trough, lies along West Rajastan, Madya Pradesh and Gangatic plains and extends up to the north Bay of Bengal (here onwards referred as 'bay') region. The location and intensity of axis of the monsoon trough plays major role in modulating the intra-seasonal fluctuations of active or weak monsoon episodes over India. The synoptic scale disturbances such as lows, depressions, cyclones etc. are normally formed in the bay region and are influenced by the fluctuations of the eastern end of the axis of the monsoon trough. After the genesis, disturbances generally move westward / west northwestward across the trough. The trough intensifies with the movement of these systems and its axis gets aligned to its normal position or shifts to the south of its normal position, resulting in a good monsoon epoch over India. Thus, to understand the monsoon activities over India, it is imperative to study the changes in atmospheric conditions over the north bay where the genesis of these disturbances take place.

The special observational program called the 'Bay of Bengal Monsoon Experiment' (BOBMEX-99), was conducted under the Indian Climate Research Programme (ICRP) during July-August 1999. The experiment was aimed at collecting data on the subseasonal variations of important variables of the atmosphere, ocean and at their interface to gain deeper insight into some of the processes that govern the variability of organized convection over the Bay of Bengal and its impact on Indian summer monsoon (Bhat et al. 2001). To obtain continuous series of observations over north bay, the research ship ORV Sagarkanya was stationed at 17.5°N and 89.0°E (hereafter refer as 'the site') during 28 July to 5 August (Phase I) and from 14 to 22 August (Phase II). This location can be considered as a representative of the atmospheric conditions over the north bay. The sea surface of the north bay was sufficiently warm and was conducive to cyclogenesis during both the phases with temperature ranging between 27.6°C and 29°C (Ghanekar et al. 2003). However, two depressions and a well marked low pressure area formed during Phase I, but no major system was developed during Phase II. In view of these anomalous features, the structure of the atmosphere is studied by analyzing the variation in the vertical profiles of the thermodynamic parameters over the site during the two phases of the experiment.

DATA AND METHODOLOGY

Indian Daily Weather Report (IDWR), All India Weather Summary and Weekly Weather Report published by India Meteorological Department (IMD) are used to study the synoptic conditions during BOBMEX-99. Table 1 summarizes the information of the synoptic scale disturbances formed during the two phases of the experiment. Day-to-day performance of the monsoon over India is assessed by computing daily values of the percentage Departure of All India Rainfall (DAIR), from its long-term normal. Similarly the meridional sea level pressure gradient, called as Zonal Index (ZI) i.e. mean sea level (msl) pressure differences between Nagpur and Thiruvananthapuram, suggests the strength of westerlies in the lower troposphere over peninsular India. The time series, of DAIR and ZI during 15 July to 31 August 1999, are analysed to examine the performance of monsoon. The time series of total cloud cover (N) and the rainfall events over the site are prepared for Phase I and Phase II. The atmospheric circulations prevailing over India and neighbouring regions in the lower and middle troposphere during the two phases are studied by utilizing the synoptic charts prepared at Weather Central, IMD, Pune. The upper air radiosonde (RS) data was acquired on board ORV Sagarkanya with special radiosonde equipment Vaisala, model RS80, by Indian Institute of Science, Bangalore. It is well known that the 00 UTC data over Indian region are free from the influence of the local convection and gives a better scenario of ensuing weather conditions. Thus, in present study the RS data for 00 UTC is analysed at each 10 hPa interval. The wind data at the site, was available for Phase II only, hence, the vertical

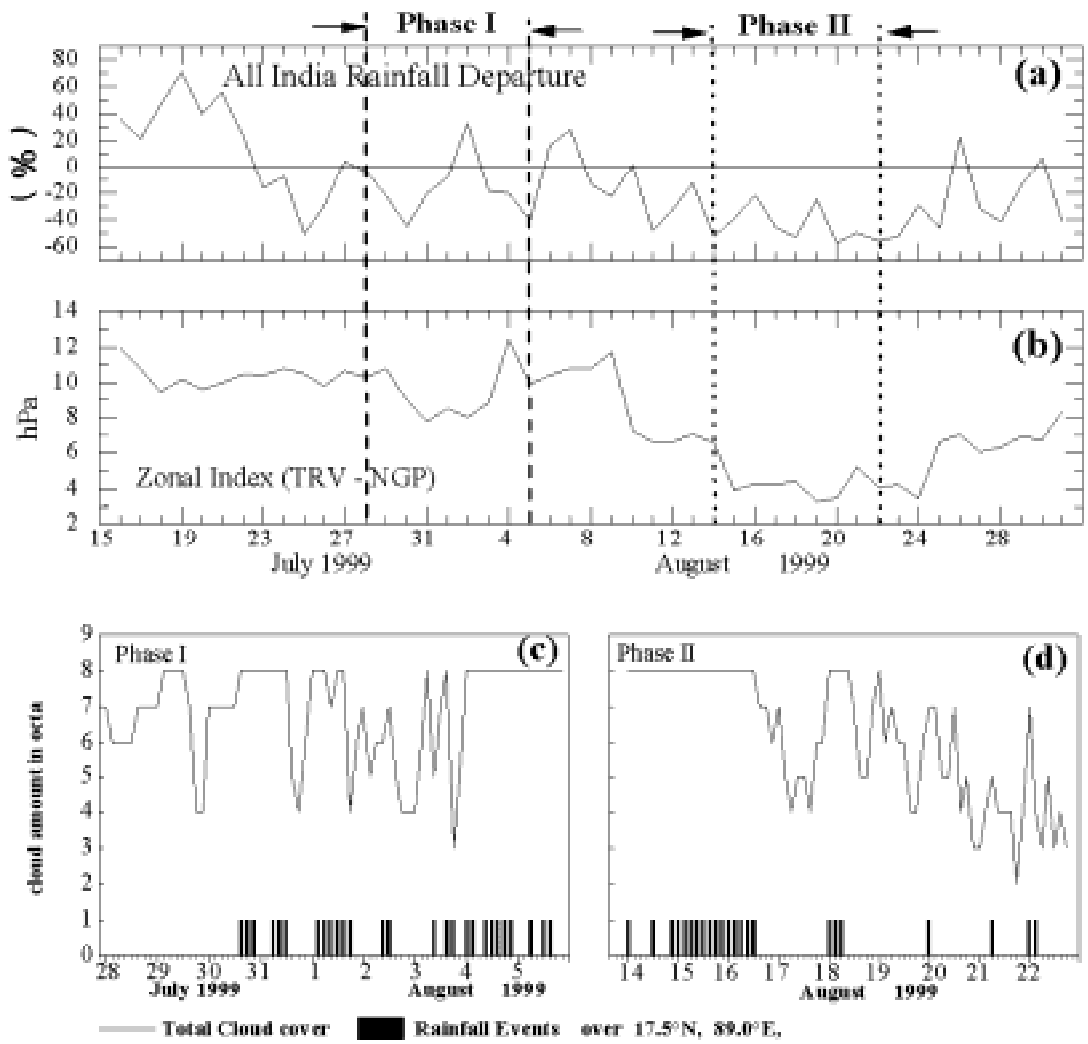


Figure 1. a) All India rainfall departure from normal in percentage during 16 July to 31 August 1999, b) surface pressure difference of Thiruvananthapuram and Nagpur (Zonal Index) in hPa during 16 July to 31 August 1999, c) total cloud cover in octas (solid line) and rainfall events over 17.5°N and 89.0°E at every 3hr interval (bar) during 28 July to 5 August 1999 and d) same as 1c but for 14 to 22 August 1999.

Table 1 : Daily location of synoptic systems during BOBMEX-99

Sr. No.	Day	Date	Time (UTC)	Type of System	Location
Phase I					
	1	25 Jul.	03	Low	NW Bay & adj. W. Bengal coast
	2	26 Jul	03	Low	-do-
	3	27 Jul.	03	D	21.0°N ; 89.0°E
	3	27 Jul.	12	DD	21.0°N ; 88.5°E
1	4	28 Jul.	03	DD	23.0°N ; 86.5°E
	4	28 Jul.	12	D	23.5°N ; 84.5°E
	5	29 Jul.	03	D	24.5°N ; 81.0°E
	5	29 Jul.	12	WL	24.0°N ; 80.5°E
	6	30 Jul.	03	WL	Madya Pradesh, adj. Rajastan & S. Utter Pradesh
	7	31 Jul.	03	L	NE Rajastan and neighbourhood
	1	31 Jul	03	CC	NW Bay off N. Orissa (extending up to midtroposphere with southward tilt)
	2	1 Aug.	03	CC	- do -
2	2	1 Aug.	12	L	NW Orissa coast
	3	2 Aug.	03	WL	NW Bay , off Orissa coast
	4	3 Aug.	03	WL	N Orissa Coast
	5	4 Aug.	03	L	E Madya Pradesh
	1	5 Aug.	03	L	NW Bay and neighbourhood
	2	6 Aug.	03	WL	NW Bay off north Orissa –W. Bengal coast
	2	6 Aug.	12	D	21.0°N ; 88.5°E
3	3	7 Aug.	03	D	22.5°N ; 88.5°E
	4	8 Aug.	03	D	22.5°N ; 87.5°E
	4	8 Aug.	12	D	22.5°N ; 85.0°E
	5	9 Aug.	03	WL	NE Madya Pradesh & neighbourhood
	6	10 Aug.	03	L	NE Madya Pradesh & neighbourhood
Phase II					
	1	15 Aug.	03	CC	Between 3.1 & 9.5 km, N. Bay & neighbourhood
	2	16 Aug.	03	CC	-do- , Central Orissa & neighbourhood
1	3	17 Aug.	03	CC	NE Madhya Pradesh & adj. Uttar Pradesh
	4	18 Aug.	03	CC	Madhya Pradesh & adj. Uttar Pradesh
	5	19 Aug.	03	CC	S. Uttar Pradesh & neighbourhood
	1	19 Aug.	03	CC	Gangatic W Bengal , up to mid-trop
2	2	20 Aug.	03	CC	Bihar Plateau
	3	21 Aug.	03	CC	E. Uttar Pradesh up to mid troposphere
	4	22 Aug.	03	CC	E. Uttar Pradesh up to 1.5 km

* Note : D = Depression DD = Deep depression WL = Well marked low L = low
CC = cyclonic circulation, N = North NW = Northwest E = East, adj.= adjoining

distribution of the wind is examined during 14 to 22 August. The various thermodynamic parameters, viz. potential temperature (θ), virtual potential temperature (θv), equivalent potential temperature (θe) and saturation equivalent potential temperature (θes) are computed upto to 300 hPa, following standard method (Bolton 1980) during the two phases.

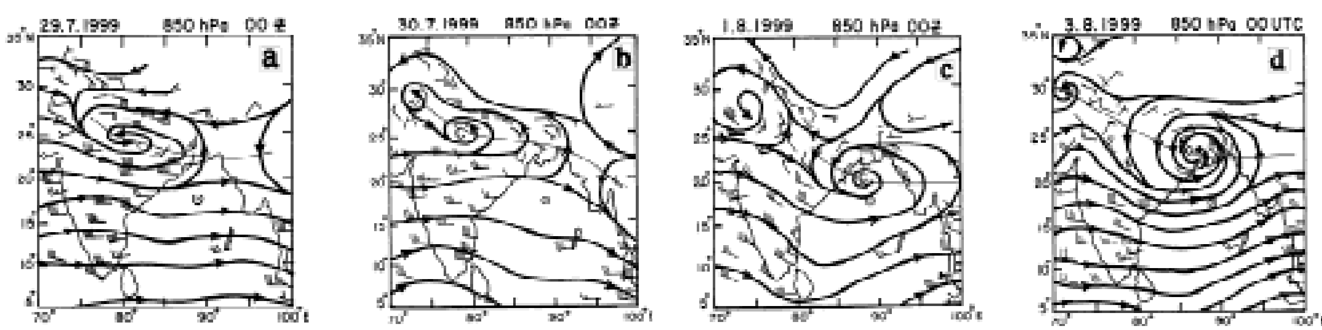
RESULTS AND DISCUSSION

Synoptic Conditions

Figures 1a and 1b show the daily variations in DAIR and ZI during 15 July to 31 August 1999 respectively. The periods of Phase I and Phase II are marked in the figures. The values of DAIRs during Phase I are either positive or above -20% of the normal, except on 30 July and 5 August when they are below -20 % of the normal. In contrast, DAIRs are below -20 % of the normal during entire Phase II (Fig. 1a). The zonal index during Phase I varied from 8 to 12 hPa, while it remained close to 4 hPa during Phase II (Fig. 1b). The high values of ZI suggest strong westerly flow linked with good monsoon activity (Paul et al. 1990). Figures 1c and 1d show the total cloud amount (N) over the site, during Phase I and Phase II respectively. The rainfall events at every 3 hour interval are marked as vertical bars in the figures. It is seen from these figures that clouds with frequent rainfall events prevailed during Phase I, while overcast skies associated with high rainfall events were observed only on 15 and 16 August during Phase II. Table 1 indicates that during Phase I three systems, viz. a deep depression, a well marked low and a depression were formed in the north bay while Phase II was affected by a single cyclonic circulation.

Figures 2 and 3 show synoptic charts for four representative days of Phase I (upper panel) and Phase II (lower panel) at 850 and 500 hPa, respectively. A dot inside a small circle(⊙), gives the location of the site. Similarly the trough is marked by a thin continuous line and the ridge by double dashed line. All the 4 days representing Phase I, i.e. 29 July, 30 July, 1 August and 3 August, show a strong westerly flow with 20 to 40 knots at 850 hPa over peninsular India and the bay region (Figs 2a-2d). Throughout this period the zonal index was high and the monsoon trough, with the embedded cyclonic circulations, remained closed to its normal position. In Phase II, the circulations at 850 hPa during 16 to 19 August

Phase I



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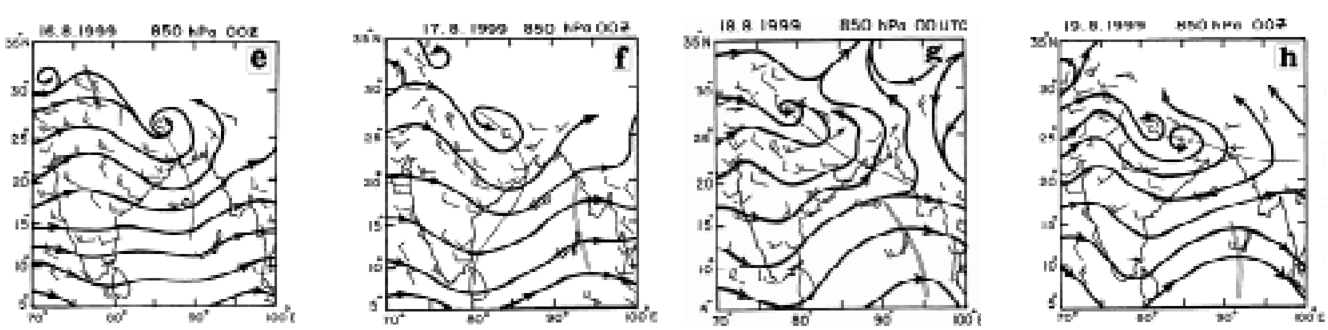

Figure 2. 850 hPa circulation at 00 UTC for a) 29 July, b) 30 July, c) 1 August, d) 3 August, e) 16 August, f) 17 August, g) 18 August and h) 19 August 1999. The site is represented by the symbol (⊙). The trough is marked by thin line and the ridge by double line.

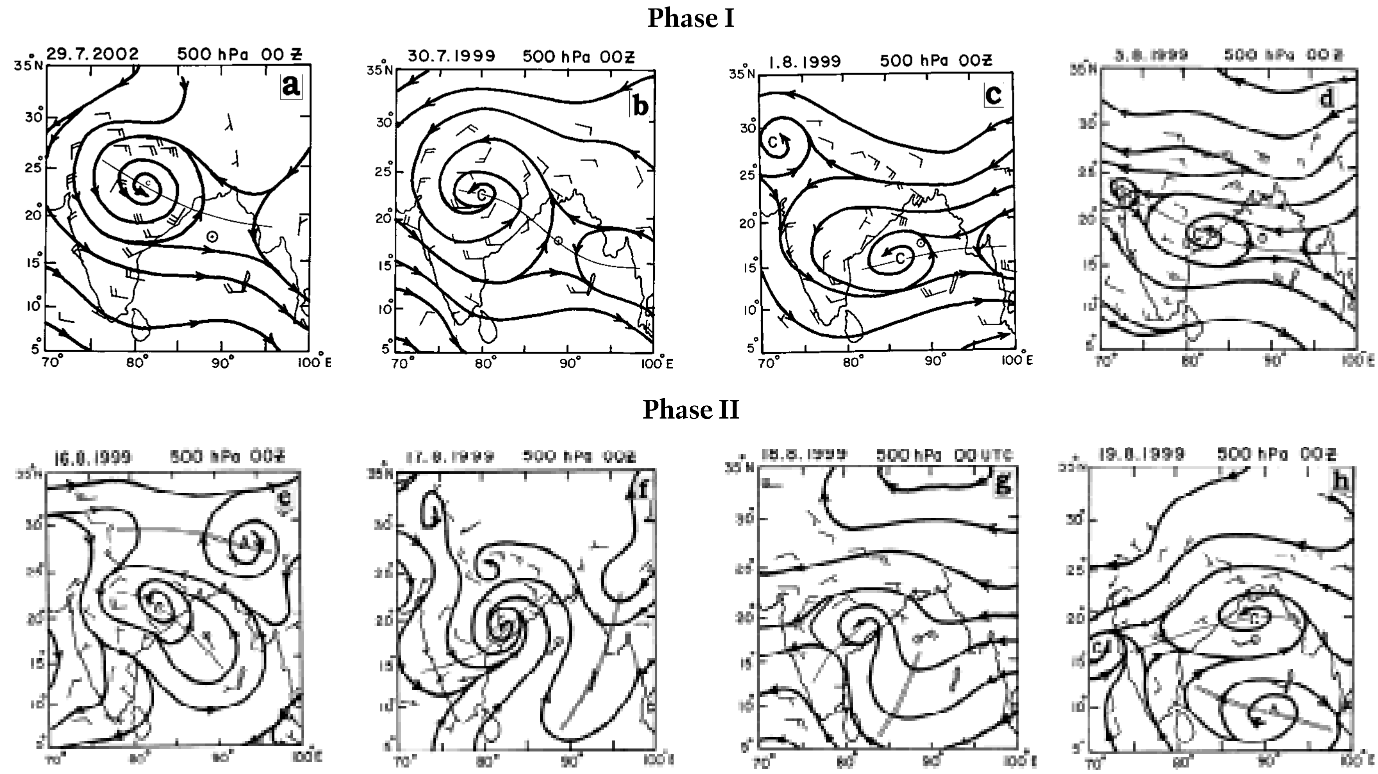

Figure 3. Same as figure 2 but for 500 hPa.

(Figs 2e - 2h) indicate comparatively weak westerlies over the peninsula. On 16 and 17 August the western part of the axis of the monsoon trough was oriented more along north-south direction (Figs 2e, 2f), resulting into a relatively weaker monsoon activity over India. Figures 2 f, g, and h, show the intrusion of a ridge from east in the bay region during 17 to 19 August.

The 500 hPa circulation show that the mid-tropospheric trough was oriented in the east-west direction across the central India, during most of the days in Phase I and its eastern end was fluctuating near the site (Fig. 3, a-d). During Phase II, the 500 hPa level was characterized by weak winds over peninsular India with a trough lying near the site on 16 and 19 August (Figs 3, e & h). On 17 August (Fig.3f) the anticyclonic circulation dominated the eastern part of bay with the appearance of ridge oriented in nearly north-south direction. The ridge moved westward on 18 August (Fig.3g) and almost entire bay region came under the influence of anticyclonic flow. An upper air cyclonic circulation was observed over head bay near the site on 19 August. However the anticyclonic circulation with near east-west ridge continued to dominate the south bay (Fig. 3h). Consequent to these events, until 16 August skies continued to be overcast with frequent occurrence of rainfall over the site (Fig.1d). The dominance of the ridge or anticyclonic circulation during 17 to 19 August at 500 hPa over the bay region resulted in the absence of cyclogenesis and gradual reduction in the rainfall towards the end of Phase II. Thus the synoptic parameters as well as the circulations at 850 and 500 hPa levels suggest an active (weak) monsoon condition during Phase I (Phase II). Ghanekar et al. (2003) have discussed the surface weather characteristics during BOBMEX-99 in details and observed similar intra-seasonal fluctuations of active and weak monsoon episodes during Phase I and Phase II.

VERTICAL CROSS SECTIONS

Winds during Phase II

Figure 4 shows vertical distribution of wind vectors over the site during 14 to 22 August 1999. The tropospheric westerly and easterly wind regimes are separated by a thick line in the figure. It is seen from the figure that strong westerly / southwesterly winds with the magnitude of 10 to 15 knots prevailed in the lower levels (between 1000 hPa and 750 hPa) on 14, 15 and 18 August. On 16 August, near the surface, winds were weak southerly, which were associated with the presence of a north-south trough in the Bay (Fig.2e). On 14, 15 and 19 August, westerly winds extended deep in to the atmosphere up to about 450 hPa level. On 15 and 16 August the midtropospheric (near 600hPa) westerlies were strong with cyclonic shear in the vertical. Also, the cyclonic circulation over the bay, in the middle troposphere was responsible for moisture convergence. A good amount of rainfall was observed over the site on these two days (Fig 1d). From 17 August till end of the Phase II, the winds in the middle troposphere were either weak westerlies or easterlies. The rainfall activity is found to be reduced from this day. The ridge extending from 850 hPa up to 500 hPa, moved in the central bay from the eastern bay and stayed close to the site on 18 August (Figs 2g and 3g). The depth of the westerlies gradually reduced to about 600 hPa on 18 August at the site and this seems to be related with the presence of ridge over the bay. On 19 August a cyclonic vortex passed over the site at 500 hPa (Fig.3h) and the depth of westerlies increased up to 425 hPa. However, as the winds were weak and vertical shear in the mid-troposphere was absent, rainfall was not observed on this day. After 19 August vertical extent of westerlies reduced to 550 hPa. The strong northeasterly winds between 600 to 400 hPa on 18 August and the persistence of the very weak wind field there after, suggests incursion of dry continental air from north towards the site. Also the circulation pattern on 18 August at 850 hPa suggests that the strong westerly winds at the site are likely to bring less moisture. In general, during Phase II, the lower troposphere initially was dominated by moist southwesterly winds. The middle troposphere showed more west to east fluctuations in wind direction as well as in wind speed. The passages of cyclonic vortices and anticyclonic ridges, from east, over the site were associated with these fluctuations. Thus reduction in cyclogenesis over the bay and weak monsoon activity prevailed over India during Phase II.

Relative Humidity (RH) and Thermodynamic parameters

The vertical time section of RH, θe, θes and Saturation Pressure level deficit (P) over the site are studied to monitor the significant changes in the thermal structure and moisture content in the lower and middle troposphere during active and weak phases of the monsoon. Daily variations in the vertical distribution of dry bulb temperatures (T) over the site (figure not presented), showed very small difference of about 0.1 to 0.3°C in the temperature profiles between surface and 750 hPa, and 450 and 200 hPa

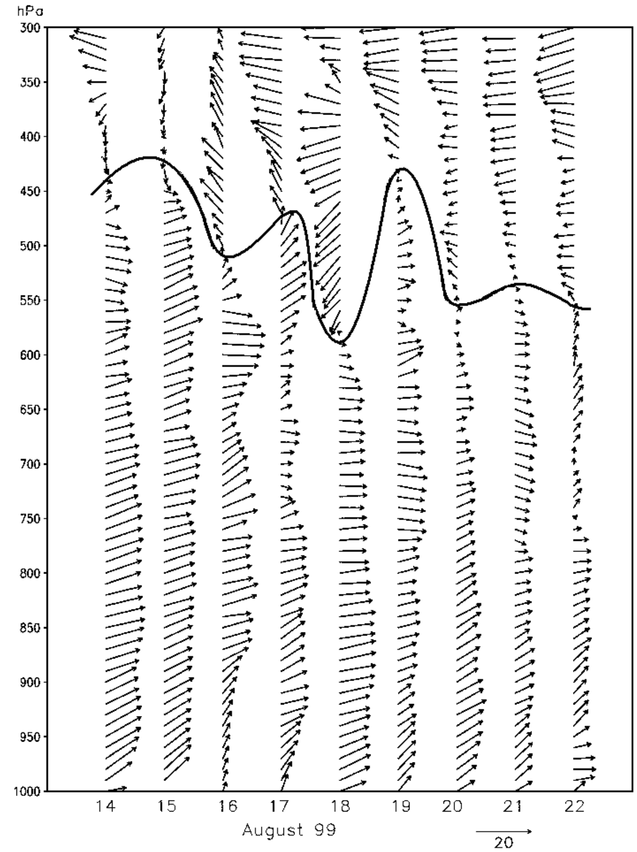

Figure 4. Vertical time section of wind vectors over the site at 00 UTC during 14 to 22 August.

during Phase I and Phase II. However, in the middle troposphere T was little higher by about 1°C during active monsoon period i.e. Phase I. Srinivasan & Sadashivan (1975) had also found very little difference in the temperature profiles of active and week monsoon periods over Visakhapatnam and Kolkata near Bay of Bengal. Gray (1970) has postulated that the latent heat of condensation, in the ascending rain producing air is stored up as an increase in potential energy and does not warm up the immediate environment. It is the compensating descending current that warms the atmosphere, but the warming is also nullified by radiational cooling. The result is that in tropics, there is a little difference in the vertical temperature distribution between rain producing and compensatory descending dry current.

Figure 5 shows vertical time section of relative humidity during Phase I and Phase II. On most of these days during the two phases, RH was more than 70 per cent upto 650 hPa. In other words moisture in the lower troposphere remained significantly high during active and weak monsoon period. However, in Phase I, the middle troposphere showed four distinct alternate spells of relatively dry (RH<80%) and moist

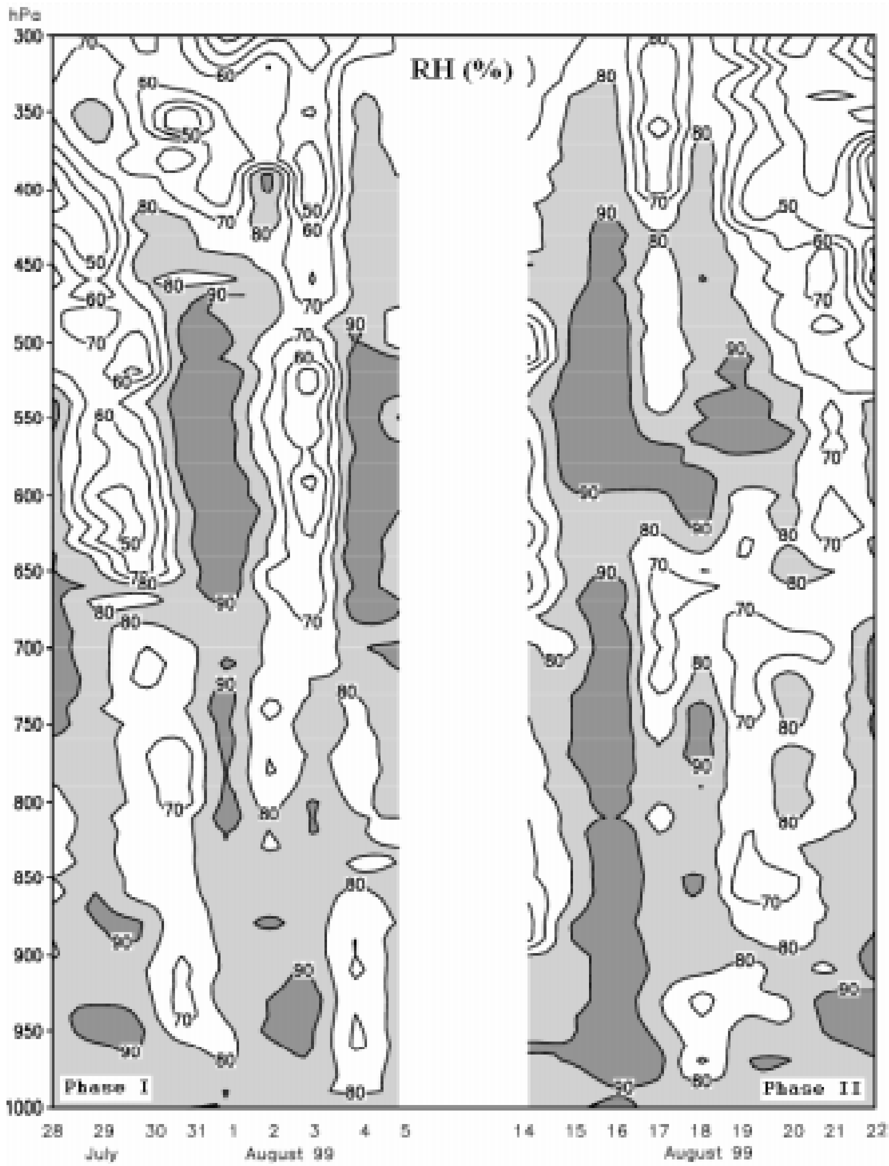

Figure 5. Vertical time section of Relative Humidity in percentage over site at 00 UTC during 28 July - 5 August 1999 and 14 – 22 August 1999.

(RH≥80%) atmosphere, viz. (i) 29 to 30 July (dry), (ii) 31 July to 1 August (moist), (iii) 2 to 3 August (dry) and (iv) 4 to 5 August (moist). The dry spells were associated with the COL that formed over the site after the passage of westward moving cyclonic systems on 29, 30 July and 3 August (Figs 3a,b,d). On these days moisture diverged from the middle troposphere leading to a decrease in RH to about 50 per cent and the rainfall reduced over the site (Fig.1c). The ship was at the proximity of the strong mid-tropospheric cyclonic circulation that was extended up to 500 hPa on 1 August (Fig.3c) and 5 August (figure not shown, refer Table 1). Under its influence RH increased above 90 per cent in the middle troposphere. These large midtropospheric RH values were conducive to vertical coupling and development of local convection and formation of systems during the period, in accordance with Gray (1975).

In Phase II, a single moist spell extending up to mid-troposphere prevailed during 15 to 17 August. On 15 and 16 August strong westerlies with cyclonic vertical shear above 600 hPa, resulted into a moisture convergence in the midtroposphere (Fig.4). The existence of a trough close to the site on 16 August (Figs 2e & 3e) accentuated the moisture incursion from surface to midtropospheric level. However, due

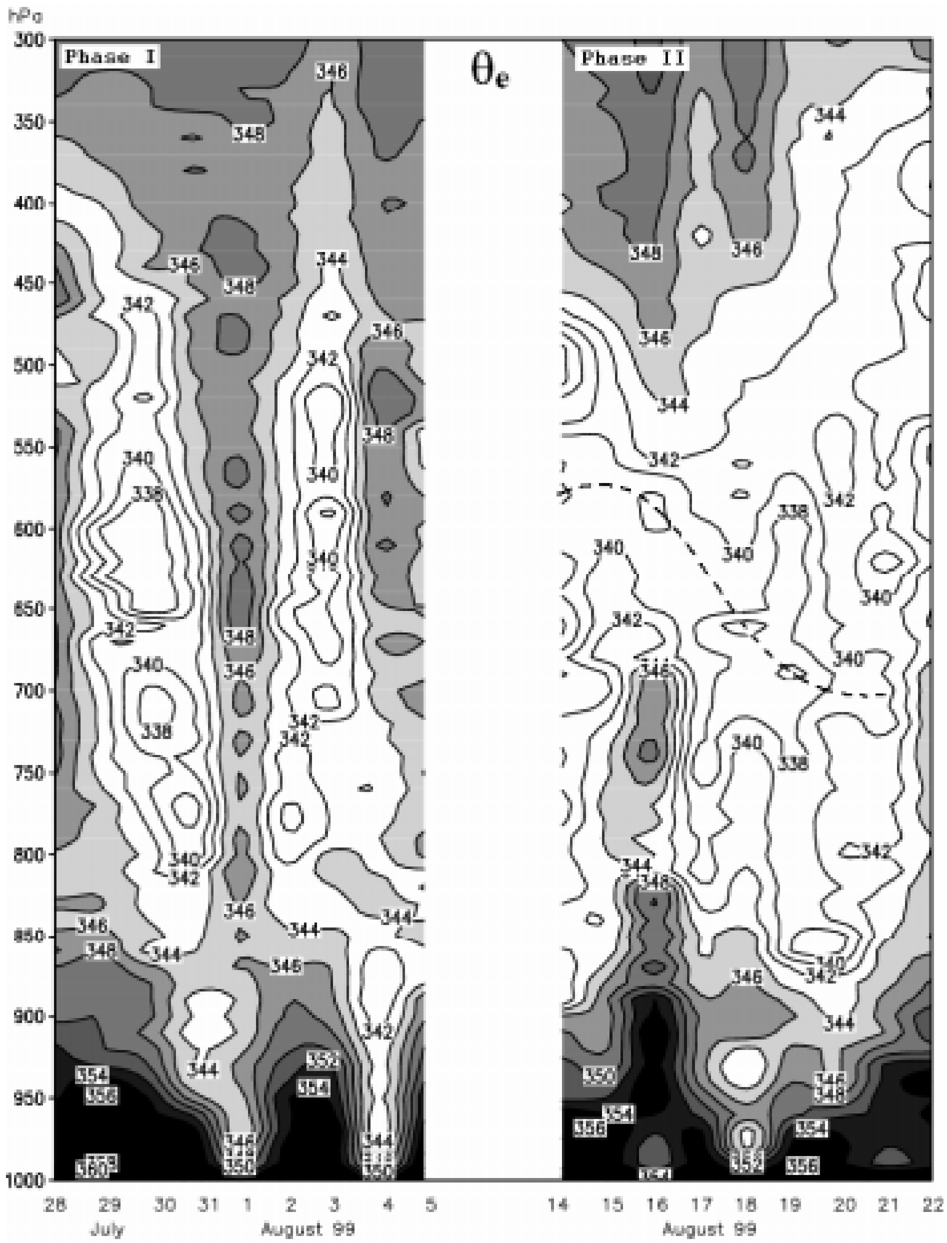

Figure 6. Same as figure 5 but for θe.

to anticyclonic vertical wind shear between 650 and 600 hPa, a small reduction in moisture was observed between these levels. Under the influence of these atmospheric conditions a heavy rainfall was experienced on the ship during 15 and 16 August. August 18 onwards a relatively dry spell continued at the site. The strong northeasterlies above 600 hPa seem to have brought in, the dry continental air over the site, resulting into the reduction in RH towards the end of the phase. Again on 19 August, appearance of a cyclonic circulation at 500 hPa level near the site (Fig.3h) temporarily increased the moisture in the mid-troposphere. The variations in the cloud cover and the rainfall events, around the 00 UTC observations, were coherent with the humidity changes in the mid-troposphere.

Equivalent potential temperature (θe) is one of the important thermodynamic parameters used to evaluate the convective instability of the environment. In tropics, θe values greater than 345K are conducive for deep convection (Betts & Ridgway 1989). Figure 6 shows vertical time section of θe over the site. θe is analyzed with 2K interval to facilitate the even contouring. The values greater than 344K are shaded

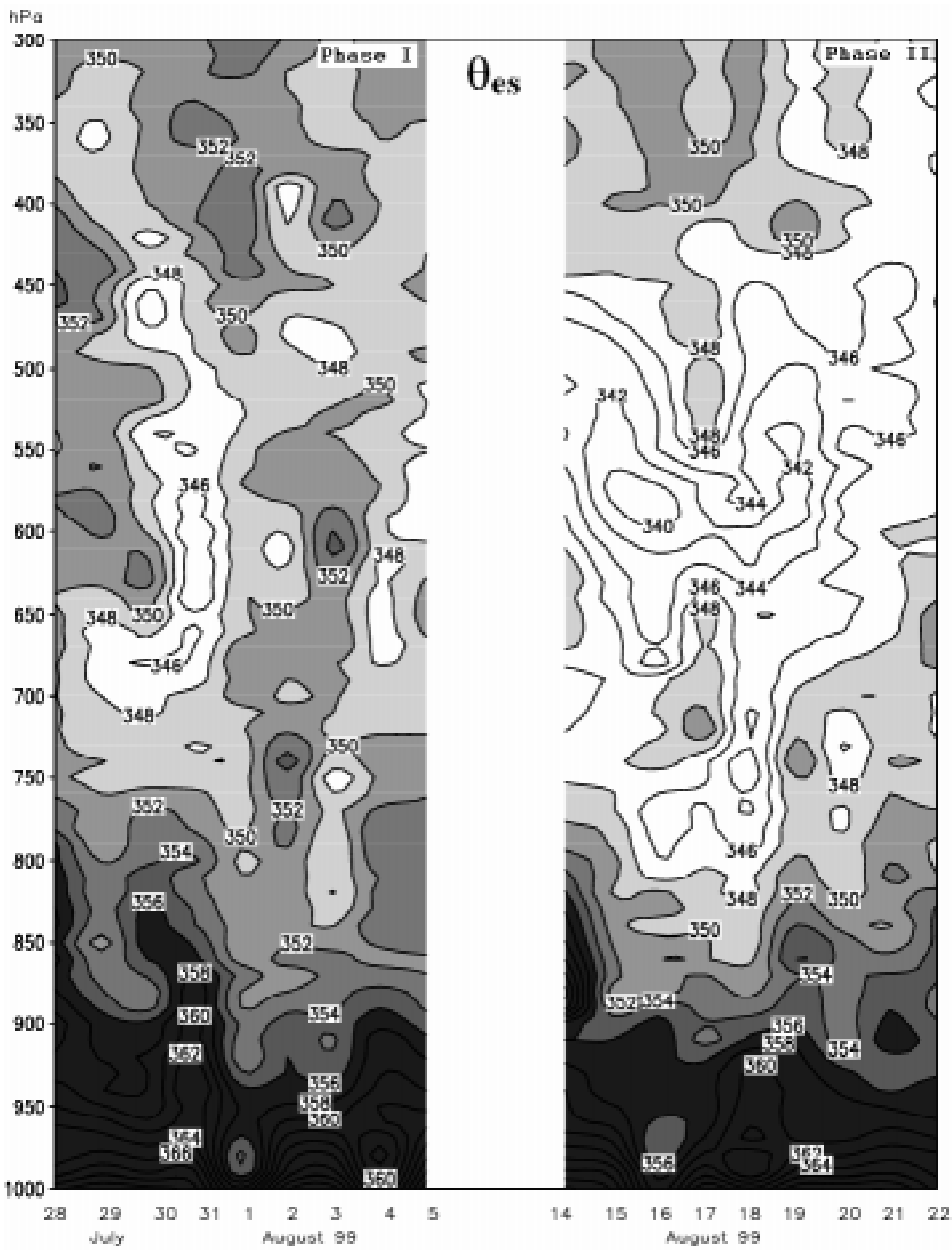

Figure 7. Same as figure 5 but for θes.

in the figure to highlight the convective regions. It is seen from the figure that during both the phases, θe varied from 360K to 344K and up to about 900 hPa, except on 31 July and 4 August in Phase I and on 18 August in Phase II. Nearly constant θe values (~348K), reaching up to the mid-troposphere around 1 August, reflect the well mixed atmosphere due to the presence of cyclonic system over the north bay. θe varied between 700 hPa and 500 hPa, from 338K to 348K during Phase I and from 336K to 344K during Phase II. During the moist spells on 1 August and 4 August, θe was greater than 348K in the mid-troposphere. Such high values were not observed in the midroposphere during Phase II. Srinivasan & Sadashivan (1975) had also observed higher θe values in the midtroposphere over various Indian stations during active monsoon days as compared to weak monsoon days.

The saturated equivalent potential temperature (θes) represents the relative drying or cooling of the atmosphere. Figure 7 shows the vertical time section of θes at the site for Phase I and Phase II. It is seen that the values of qes were higher than 350K from surface to 850 hPa during both the phases. These high values of θes penetrated deep in to the mid-troposphere

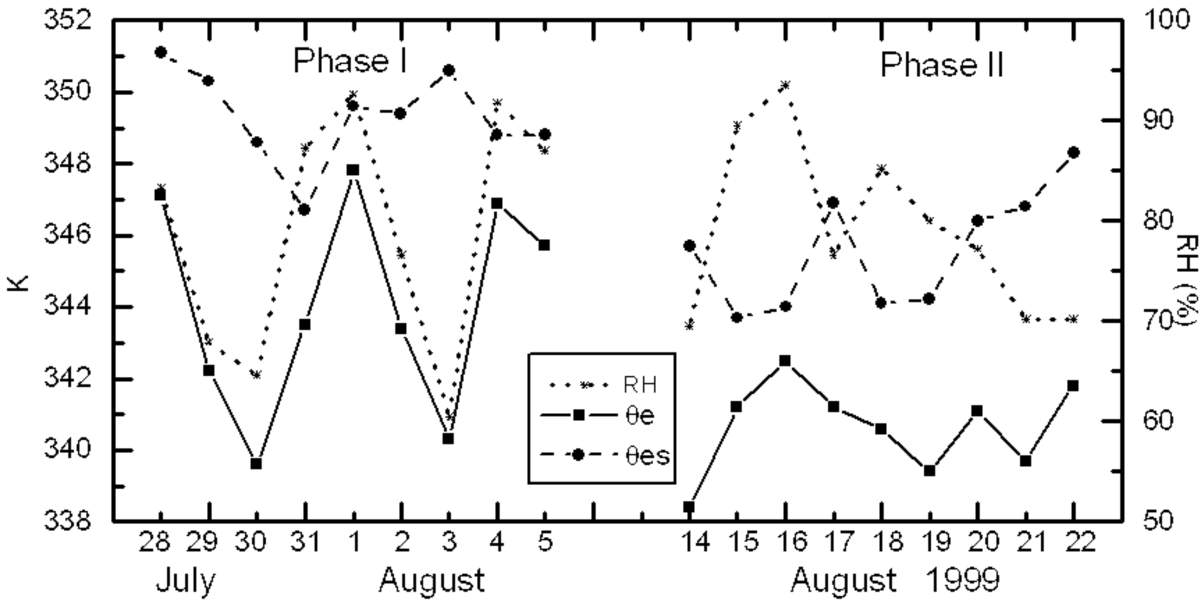

Figure 8. Time section of RH, θe, θes during Phase I and Phase II averaged for the levels between 700 hPa and 450 hPa.

during moist days of Phase I. On 30 July and 3 August θes reduced, suggesting cooling of the atmosphere between 700hPa and 400 hPa, in association with the presence of COL over the site at 500 hPa level. During Phase I, θes exhibited more day to day variation ranging from 346K to 354K, without much significant vertical gradient between 650 hPa and 500 hPa. However in Phase II, θes fluctuated between 340K and 348K in the middle troposphere with high vertical gradient and less day to day variations. Taking into consideration the existence of high moisture (RH>75%) throughout the Phase II in the midtroposphere (Fig. 5), these relatively low θes values suggest comparatively cooler atmosphere. It is observed that on heavy rainy days of 1, 15 and 16 August, the θes at lower levels has decreased significantly, there by suggesting cooling of convective boundary level by evaporation of falling precipitation (Betts 1982). However, such significant decrease in θes at the lower levels is not observed on rainy days of 4 and 5 August.

Figure 8 shows daily variations of the average RH, θe and θes for the levels between 700hPa and 450 hPa during Phase I and II. On the days when the monsoon activity was relatively weak during Phase I, i.e on 29-30 July and 2-3 August, the structure of the atmosphere was characterized by relatively drier midtroposphere (low θe) with moist base at lower levels (RH>80%). Similarly during active days of 31July-1August and 4-5 August, the mid-troposphere remained highly moist and cloudy with relatively drier base (RH<80%, Fig. 5). It suggests pumping of lower tropospheric moisture into the middle troposphere in the formative stage of synoptic scale disturbances with highly convective atmosphere. It is observed from the figure that the difference between θes and θe is quite low (<2K) during moist spells while it is relatively high (~ 6-10K) during dry spells. θe in the middle troposphere has oscillating nature with high amplitude during phase I while it has relatively less fluctuations with low values and small amplitudes during Phase II.

The saturation pressure deficit (P = p*- p) of an air parcel specifies the thermodynamic state of the air parcel and identifies the cloud layers. It is defined as the pressure difference between saturation level pressure (p*) and initial level pressure (p) of an air parcel and can be determined by dry adiabatic ascent of an unsaturated air parcel, to a pressure level where it gets just saturated with the available moisture. According to Betts (1982) small negative values of P (≥ -20hPa) corresponds to the layers closer to the saturation and of extensive cloudiness. The large negative values of P (< -20hPa) suggests lack of saturation i.e. sub-saturation. Figure 9 shows vertical time section of P at the site during Phase I and Phase II. Very small negative values of P (P>-20hPa) between the levels 650 hPa and 400 hPa, during moist spells of Phase I i.e. (31July-1August and 4-5 August), suggest the existence of thick cloud layer in the middle troposphere. The dry spells during 29-30 July and 2-3 August are characterized by large negative P (P<-30hPa) almost over the entire troposphere. The

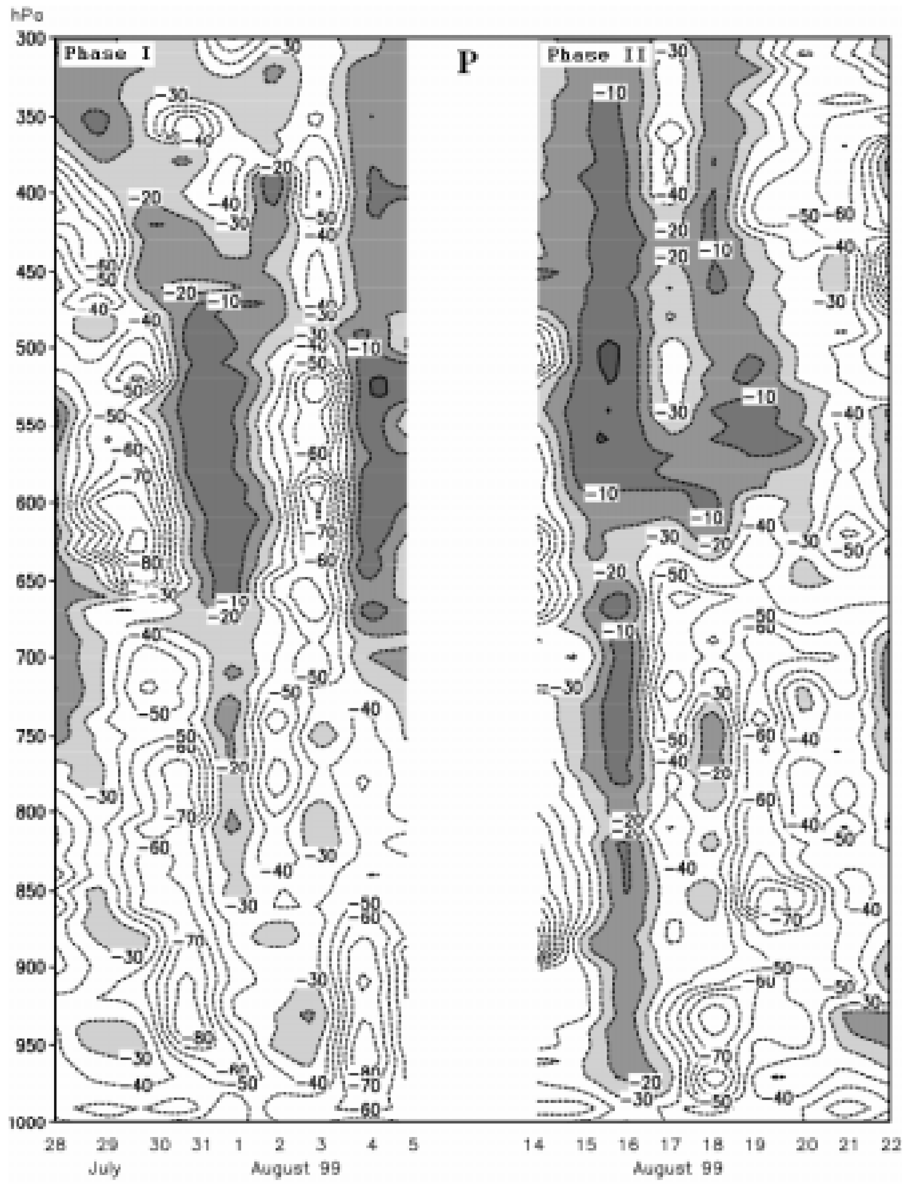

Figure 9. Same as figure 5 but for Saturation Pressure Deficit P.

reduction of moisture was resulted by the divergence of air due to the existence of a COL near the ship location. Very small negative P values in the lower troposphere and simultaneous existence of large negative P in the middle troposphere suggest the building up of moisture in the lower troposphere, just prior to the formation of the disturbances (e.g. 29-30 July and 2-3 August). During Phase II the lower troposphere was dominated mostly by large negative P values except for 16 August. On 16 August small negative P values extended from surface up to 300 hPa when the trough of low was seen over the bay on 850 hPa and 500 hPa level charts (Figs 2e & 3e). On 19 August, small negative values of P around 550 hPa and 500 hPa were associated with the convergence of moisture due to appearance of midtropospheric cyclonic circulation near the site (Fig.3h).

It is interesting to compare the nature of the thermodynamic parameters of the atmosphere during active and weak phases of the monsoon. However, the vertical profiles of RH during the active and weak phases of the monsoon show large day to day variations in the moisture content of the atmosphere over the site. Hence, grouping of the thermodynamic parameters for the entire Phase I and entire Phase II may involve combination of radiosonde ascents passing through relatively moist and dry atmospheric condition. The averaging of such a group may not represent the characteristics of active or weak monsoon phase properly. In view of this, only days of the 'moist ascents' are selected by careful examination of daily profiles of RH during the two phases. The ascent for the day is considered as the 'moist ascent', if on the day, more than 70% of RH extends upto 400 hPa and the day is also associated with the rainfall over the site either during the ascent or 3 hours prior to or after the ascent. RH, θv, θe, and θes for the days of moist ascents during Phase I (viz. 31 July and 1, 4 and 5 August) and during Phase II (viz.13, 14 and 16 August) are averaged separately and marked by suffix I and II respectively. Then these two profiles for each of the parameters are compared. The average RH profiles for moist ascents during the two phases (RH_I and RH_{II}), thus show, more than 70% of relative humidity upto 400 hPa (Fig.10a), with RH_I remaining relatively greater than RH_{II}. However near the surface RH_I and RH_{II} are almost equal upto 950 hPa and RH_I is smaller than RH_{II} by about 5% near 600 hPa. This shows that the atmosphere over the site during the moist ascents of Phase I, was relatively more moist

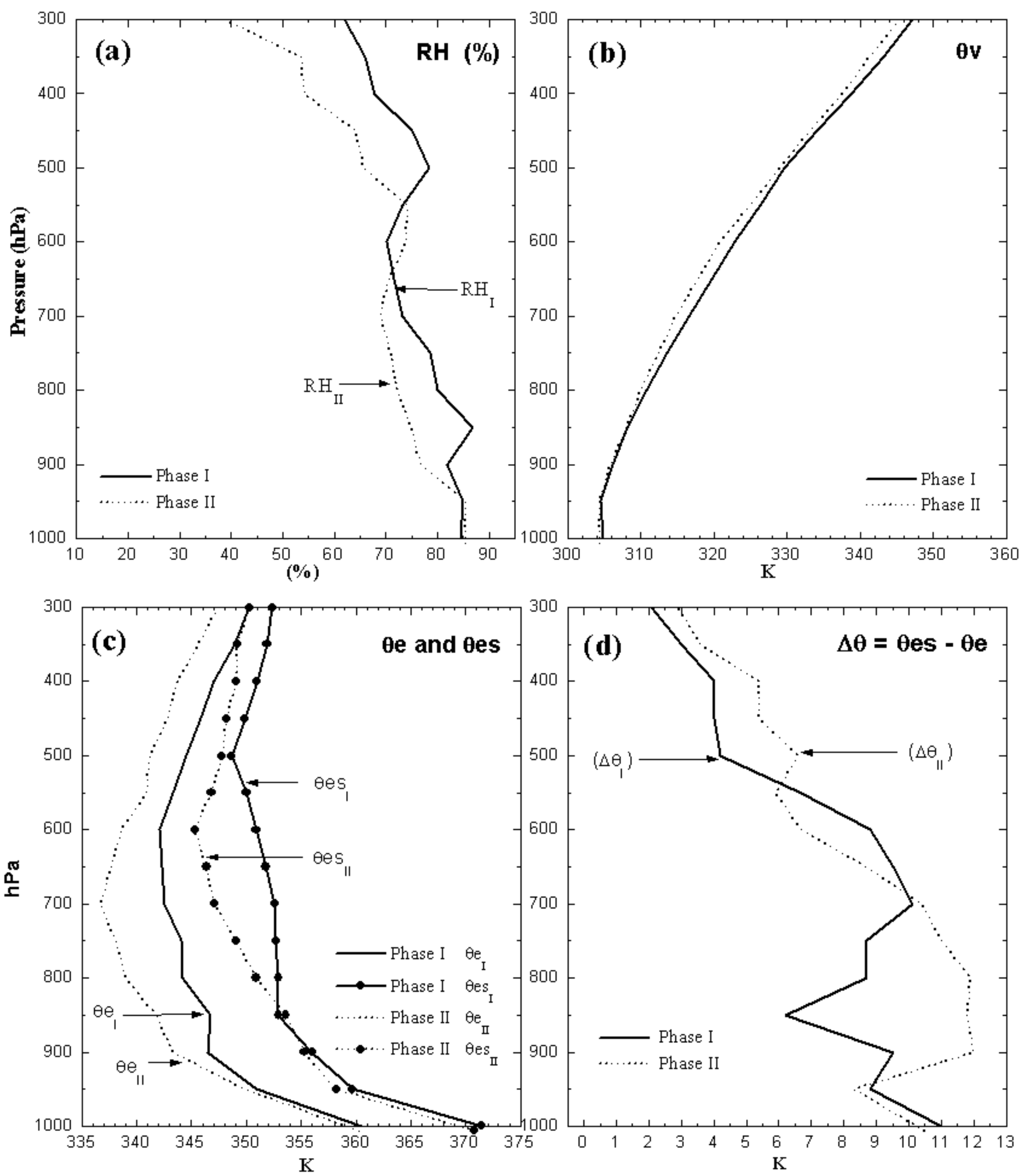

Figure 10. Average vertical profiles of the a) RH, b) θv, c) θe and θes and d) Δθ = θes – θe, for the moist ascents during Phase I and Phase II .

than Phase II. The structure of the average virtual potential temperatures θv_I and θv_{II} was nearly same up to the middle troposphere with a maximum difference (θv_I - θv_{II}) of about 2.5K near the 600 hPa (Fig.10b).

Figure 10c shows average profiles of θe and θes during the moist ascents of Phase I (θe_I and θes_I) and Phase II (θe_{II} and θes_{II}). The high values of θe_I and θe_{II} (>345K) with large negative gradient up to 900 hPa suggests existence of warm, unstable and highly covective atmosphere near the surface, which was conducive to the cyclogenesis during the two phases (Betts and Ridgway, 1989). The figure shows further decrease in θe_I up to 600 hPa and in θe_{II} up to 700 hPa, with the intermittent layers of near constant values of θe_I between 900 hPa and 600 hPa. The layers of near constant θe_I values indicate multilayer structure of the clouds below 600 hPa. Whereas, minimum θe_I at 600 hPa (342.1K) and minimum θe_{II} (336.7K) at 700 hPa (336.7K) suggests that the depth of convective instability was lower in Phase II than Phase I (Betts 1982). Small kink in θe_{II} at 550-500 hPa clearly indicates subsidence from above and mixing with environment during Phase II.

The values of θes are near equal up to 850 hPa during the two phases. Whereas, above 850 hPa, θes_I is higher than θes_{II} with maximum difference of 5.5K between the layers 650 hPa and 600 hPa. The high values of θes_I can be attributed to the release of latent heat due to more rainfall during the active atmospheric condition of Phase I. However θes_I is nearly constant between 850hPa and 750 hPa while θes_{II} shows decreasing trend with minima at 600 hPa. In the present case of moist ascents, very small difference of RH in the lower and middle troposphere during the two phases and higher values of θe and θes in the midtroposphere during Phase I (i.e. $\theta e_I > \theta e_{II}$ and $\theta es_I > \theta es_{II}$) suggests significantly warmer mid-troposphere during Phase I as compared to Phase II.

Figure 10d shows the vertical profile of Δθ (= θes - θe) for the two phases i.e. $\Delta\theta_I$ (= θes_I - θe_I) and $\Delta\theta_{II}$ (= θes_{II} - θe_{II}). This parameter is a measure of sub-saturation of the atmosphere (Betts 1974, Tyagi, Nagar & Seetharamayya 1999). The two profiles show no appreciable difference up to 950 hPa, suggesting near equal degree of saturation between the two phases near the surface. The values of $\Delta\theta_I$ are lower than $\Delta\theta_{II}$ between 950 hPa and 700 hPa and 650 hPa and 300 hPa indicating relatively more saturation during Phase I. The multilayer clouds with very low $\Delta\theta_I$ at 850 hPa coincides with the sudden increase in RH seen at the same layer during Phase I (Fig.10a). Very low and constant values of $\Delta\theta_I$ between 500 hPa and 400 hPa indicate high convection with presence of convective clouds in the midtroposphere during Phase I. Similarly constant and very high values of $\Delta\theta_{II}$ between 900 hPa and 800 hPa represent well mixed lower layer with clouds of lower depth and comparatively less moist convection in Phase II. The comparatively high values of $\Delta\theta_I$ than $\Delta\theta_{II}$, between 700 hPa and 600 hPa can be attributed to the drying effect of downdraft during the wake of high precipitation caused by the synoptic scale disturbances during Phase I.

Gadgil (2000) has suggested that the deep convection in the tropics can be maintained only when there is positive cloud buoyancy over a large depth of the atmosphere and buoyancy of cloud depends not only on the properties of air near the surface of the ocean but also on those of the upper air through which it rises. From the circulation patterns at 850hPa (Fig.2) and 500 hPa (Fig. 3) and the vertical distribution of θe and θes (Fig. 6 and 7), it is clear that the atmospheric conditions over the site were conducive to cyclogenesis through convergence of moisture in lower and middle troposphere during Phase I. The air parcel that might have been forced upward remained buoyant during Phase I. Whereas, moisture convergence took place due to weak winds at 850 hPa over the site during Phase II. The zonal circulation over peninsular India in Phase II was weak and the orientation of monsoon trough was rather abnormal at 500 hPa. The sudden change in 500hPa circulation pattern, from 18 August onwards (Figs. 3 g,h and 4), inhibited the moisture incursion and suppressed the development of deep convection during Phase II.

CONCLUSIONS

The analysis of circulation patterns and rainfall activity over the Indian subcontinent and the thermodynamic parameters of the atmosphere over the north Bay of Bengal at 17.5°N, 89.0°E during BOBMEX-99 reveals that the Phase I and Phase II of the experiment coexisted with active and weak periods of Indian summer monsoon respectively. The analysis further shows that the large scale circulation features over the Indian region are mainly responsible for the intensification or suppression of disturbances over the Bay of Bengal, which leads to active or weak monsoon condition over India. The significant impact of the circulation is observed in the variation of the thermodynamic characteristics in the middle troposphere over the north bay. During the two phases of the experiment θe values over the site remained greater than 345K suggesting favourable condition for in-situ formation of cyclogenesis. However, two depressions and one well marked low pressure area formed during Phase I, while, only a single cyclonic circulation between 3.1 and 9.5 km formed during Phase II. In association with the rapidly changing atmospheric conditions over the bay during Phase I, large fluctuations in the thermodynamic parameters are observed in the middle troposphere at the site. The comparison of mean profiles of θe and θes, for moist ascent of the two phases, show cooler midtroposphere during Phase II suggesting suppressed convective activity. The change in the mid-tropospheric meridional wind component from southerly to northerly on 17 and 18 August, subsequently accentuates the suppression by the advection of dry continental air over north bay leading to weak convective activity over the region. Moreover, the inhibition of cyclonic circulation in Phase II at 500 hPa appears to have suppressed the formation of disturbances over the bay region, even under the favourable sea surface conditions. The experiment has given a rare opportunity to study the behaviour of atmosphere over the Bay during the two contrasting phases of the monsoon. However, more such case studies are required to be carried out to confirm the role of mid-tropospheric circulation and the thermodynamic variations over Bay of Bengal during active and weak phases of monsoon.

ACKNOWLEDGMENTS

Authors are extremely thankful to Dr. G.B. Pant, the Director, Indian Institute of Meteorology for nominating Mr. V.R. Mujumdar and Mr. S.P. Ghanekar to participate in the BOBMEX-99 field experiment and for the encouragement. Authors are also grateful to India Meteorological Department and Indian Institute of Science, Bangalore for providing valuable data.

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(Accepted 2005 April 8; Received 2005 March 4; in original form 2004 July 22)

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