

Conserved variable and observational analysis over the West Coast of India during ARMEX-2002

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सार – इस शोध-पत्र में अरब सागर मानसून प्रयोग (आरमेक्स) के दौरान मानसून और संबद्ध संवहनी सक्रियता का विवेचन किया गया है तथा विशेष रूप से भारत के पश्चिमी तट पर मानसून के आरंभ की प्रक्रियाओं और तीव्र वर्षा की घटनाओं के विषय में चर्चा की गई है। इस शोध-पत्र का मुख्य उद्देश्य भारत के पश्चिमी तट पर आरमेक्स के दौरान लिए गए धरातलीय और उपरितन वायु प्राचलों में पाई गई परिवर्तनशीलता का अध्ययन करना है। इस अवधि के दौरान भारत के पश्चिमी तट के साथ-साथ संवहनी रूप से सक्रिय और निष्क्रिय क्षेत्रों में धरातल से लेकर परिसीमा स्तर के 3 कि.मी. तक के प्रत्येक प्वाइंट पर विभव तापमान, वास्तविक विभव तापमान, समान सांद्रण विभव तापमान और विशिष्ट आर्द्रता आदि के सुनिश्चित परिवर्तनशील विश्लेषण (सी. वी. ए.) भी किए गए हैं। महासागर अनुसंधान पोत सागर कन्या के मार्ग में समुद्र सतह तापमान (एस. एस. टी.) वायु तापमान, पवनगति और नमी जैसे सतह प्राचलों के विश्लेषण किए गए हैं। पश्चिमी तट के कुछ स्थलीय स्टेशनों जैसे कि विजयदुर्ग, करवाड़, होनावर और गोवा में भी इसी प्रकार का विश्लेषण किया गया। निम्न वायुमंडल को प्रभावित करने वाले कारकों के कारण परिसीमा स्तर की संरचना में परिवर्तनशीलता पाई गई तथा भारी वर्षा की घटना से एकदम पहले की सक्रिय संवहनी प्रक्रिया के दौरान परिसीमा स्तर की ऊँचाई में विशेष वृद्धि होने की सामान्य प्रवृत्ति रही है।

ABSTRACT. The Arabian Sea Monsoon Experiment (ARMEX) addresses monsoon and associated convective activity, laying emphasis on the monsoon onset processes and intense rainfall events over the west coast of India. The prime objective of this paper is to study the variation observed in the surface and upper air parameters obtained over the west-coast of India during ARMEX. Conserved Variable Analyses (CVA) of *viz.*, potential temperature, virtual potential temperature, saturation equivalent potential temperature and specific humidity etc. were also carried out at every point up to 3 km from the surface to cover the boundary layer over convectively active and suppressed regimes along the west-coast of India during this period. Analyses of the surface parameters such as sea-surface temperature (SST), air temperature, wind speed and moisture along the ORV Sagar Kanya (ORVSK) cruise track were carried out. Similar analysis was also carried along a few of the west-coast land stations *viz.* Vijaydurg, Karvar, Honavar and Goa. The structure of the boundary layer was found to be varying depending on the various factors that influence lower atmosphere and the general trend being a pronounced increase in the boundary layer height during an active convection process just before the heavy rainfall event.

Key words – ARMEX, Boundary layer height, Conserved variable analysis.

1. Introduction

BOBMEX observations carried out in June-August 1999 clearly brought out the variability of planetary boundary layer (PBL) and related convective activity during the summer monsoon (Bhat *et al.*, 2001, Bhat, 2003, Sam *et al.*, 2003 and Mohanty *et al.*, 2003) over the Bay of Bengal.

The second field experiment under the ICRP implementation plan (DST, 1998) was the Arabian Sea

Monsoon Experiment (ARMEX) that was carried out in two phase *viz.*, ARMEX-I and II. These experiments were focused towards understanding the realities in the coupled ocean-atmosphere and land-surface processes involved in the genesis and intensification of the systems responsible for such intense rainfall episodes over the west coast of India as well as in understanding the warm pool in the south east Arabian Sea during March to May period. The high rainfall over the west coast and the heavier rainfall over the Western Ghats are generally attributed to the forced ascent over the present orography. However, it is

the experience of the forecasters that on several occasions when the rainfall is heavy at the coastal stations, several stations on the Ghats do not get heavy precipitation (Mukherjee *et al.*, 1978). Such a distribution of precipitation probably arises from a combination of factors including synoptic and meso-scale systems as well as orography. It has been also suggested that the systems associated with coastal rainfall are offshore troughs (Rao, 1976). However, it is not yet clear whether the offshore trough results from the Arabian Sea convection or is a factor promoting the offshore convection. Offshore troughs have on occasion, vortices embedded on them called the offshore vortex.

2. Synoptic situation during ARMEX – I (2002)

Year 2002 seasonal rainfall (June-September) for the country as a whole was 19% below normal (IMD report, 2002). The behavior of the 2002 SWM has evoked a lot of questions. Its onset over Kerala was on time but it reached northwest India only by mid-August. The month of June observed above normal rainfall but July recorded the lowest rainfall in history. There was some recovery in August. Although 2002 was a drought year, there were spells of heavy rainfall events over the coastal stations of western India, both in June and August 2002, while a prolonged break period characterized the month of July 2002. The variation in the surface, and upper air meteorological parameters associated with the intensification and weakening of convective processes along the west coast during ARMEX-I was the focal point of this study. Goa (15.38° N, 73.83° E) was one such west coastal station where Vaisala sondes were used by Indian Navy as a part of ARMEX – I, to procure high-resolution vertical profiles of temperature, specific humidity, wind speed and direction. Automatic Weather Station (AWS) were also installed at Goa along with other west coast land stations *viz.*, Karvar, Vijaydurg, and Honavar for regular record of the surface parameters.

3. Data and analysis methodology

Surface meteorological parameters such as wind speed, wind direction, sea surface temperature (SST), dry-bulb and wet-bulb temperature and cloud cover, collected onboard ORVSK over the Arabian Sea along the west coast of India from 24 June – 15 August 2002 and at Goa (19 June – 10 August 2002) are used for CVA in the present study. In addition to these data, surface observations obtained from AWS at Goa, Karvar, Vijaydurg and Honavar are also analysed to see if there is any significant variability that could have affected the SWM.

3.1. Conserved variable analysis

Betts and Albrecht (1987) give an idealized illustration of CVA depicting the importance of the Conserved Variable Diagrams. A schematic mixing line after them is shown between Saturation Points (SPs) of the well mixed sub-cloud layer and the CBL top on a (θ_e , q) diagram. The q (specific humidity) axis for the unsaturated air has been reversed so that a sounding data plotted on this diagram resembles more familiar (θ_e , p) plot. In the absence of irreversible diabatic processes, variables represented on both the axes are conserved. θ_e (equivalent potential temperature) or q is not changed during condensation process, whereas, the precipitating process moves the parcel points to lower q at constant θ_e (and the reverse for the evaporation of falling precipitation). The radiative process does not change q , but radiative cooling moves SPs to lower θ_e at constant q . Mixing lines are straight lines and advective processes do not move the parcel points at all. The thermodynamic changes represented by the triangular path shows precipitation in the ascending deep convective branch of the tropical circulation which moves the parcel from the sub-cloud layer to lower q , at constant θ_e . Radiative cooling in the subsiding branch lowers θ_e at constant q . The air with the lowest θ_e sinks into the CBL and its SPs move down the mixing line as it is mixed with air from below on its final mean descent back into the sub-cloud layer.

3.2. Marine Boundary Layer Height (MBLH)

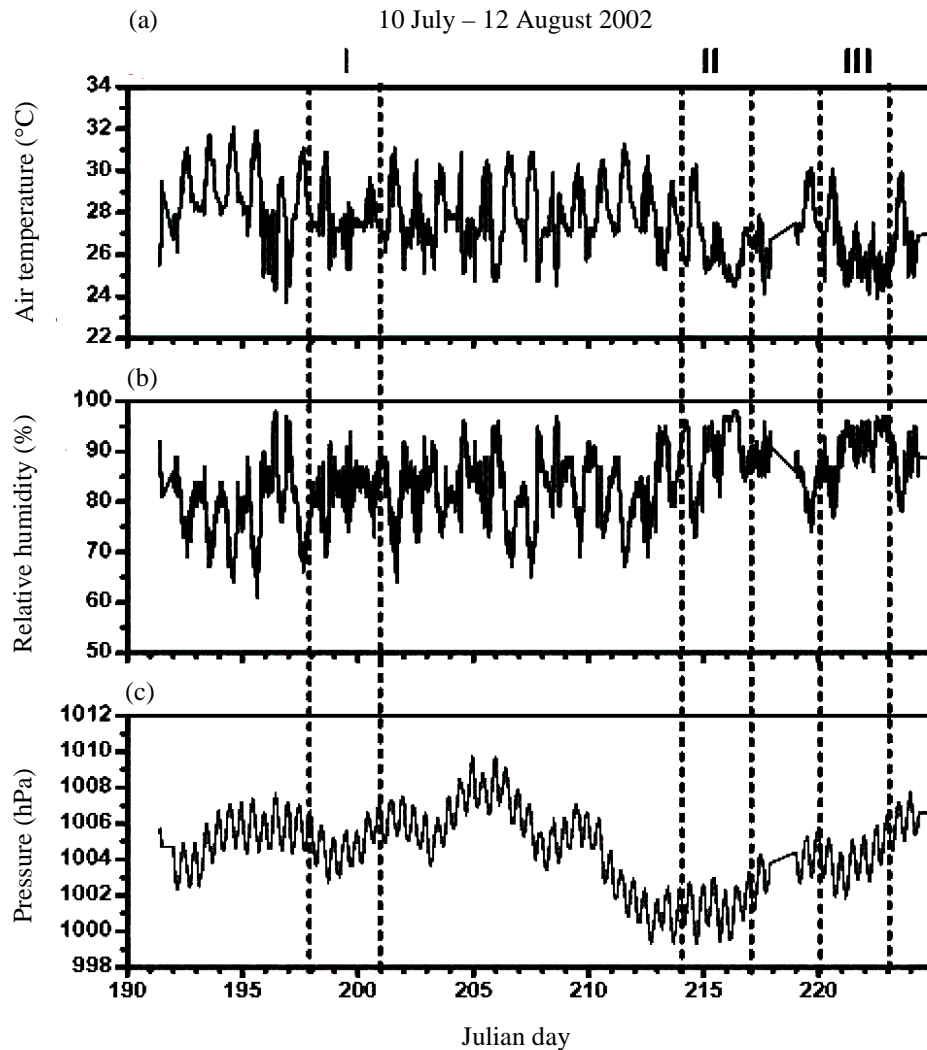
Vertical profiles of θ_v , θ_e and θ_{es} are drawn to estimate the MBLH. The MBLH is marked by minimum θ_e and maximum θ_{es} .

3.3. Static stability analysis

Dry static energy (S) is a thermodynamic variable similar to potential temperature, except that the concept of static energy assumes that any kinetic energy is locally dissipated into heat. The amount of this dissipative heating is often negligible. S is calculated using the expression :

$$S = C_p T + gz$$

Where, C_p is the specific heat at constant pressure for moist air, T is the temperature, g is the acceleration due to gravity, z is the height above m.s.l. The partial change in S with respect to z , *i.e.*, $\partial S/\partial z$ determines the dry static



Figs. 1(a-c). Variation of surface parameters at Vijaydurg (a) Air temperature (°C), (b) Relative humidity (%) and (c) Surface pressure (hPa)

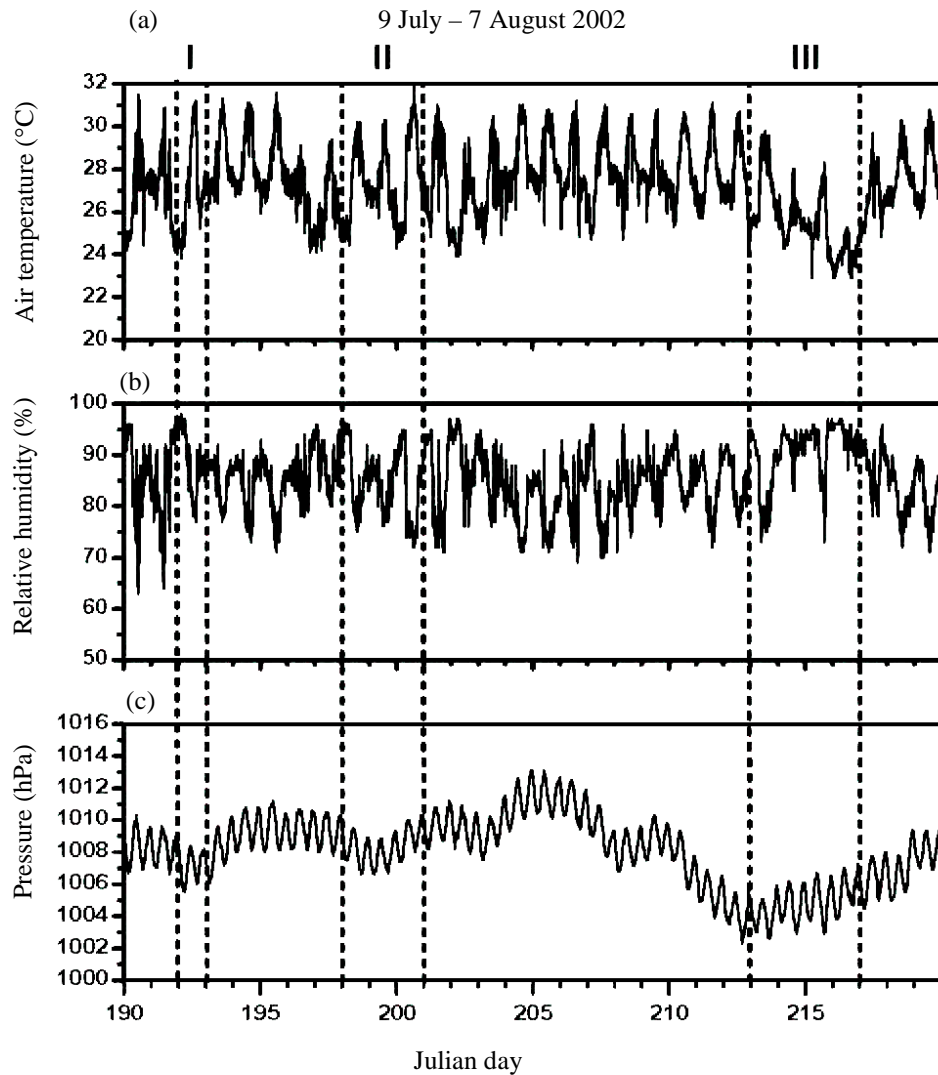
stability. Stable atmosphere is characterized by the negative gradient of $\partial S/\partial z$.

4. Results and discussion

4.1. Variation of surface meteorological fields along the west coast of India

Figs. 1-3, describe the variations observed in surface pressure, temperature and relative humidity over the west coast land stations *viz.*, Vijaydurg (16° N, 73° E), Karvar (14.8° N, 74° E) and Honavar (14.4° N, 74.5° E) respectively. Examination of daily rainfall occurrence over these stations taken from the ARMEX weather summary (Mohanty *et al.*, 2002) indicates a weak rainfall

event in July 2002 (198-201 Julian Days). Figs. 1 (a-c) represents the surface variability of air-temperature [Fig. 1 (a)], relative humidity [Fig. 1 (b)] and surface pressure [Fig. 1 (c)] at Vijaydurg from 10 July – 12 August 2002. Careful exploration of these plots reveal distinct variability wherein three periods (I : 198-201, II : 214-217 and III : 220-223 Julian Days) of active convection with rainfall activity could be delineated. These periods correlate well with the synoptic observations made in the ARMEX weather summary. During the II and III period at Vijaydurg, the relative humidity [Fig. 1 (b)] rises to almost 98% while during the I period an average of 85% was noticed. The surface pressure dropped 2 hPa during the I period while during the II period the surface pressure went as low as 1000 hPa

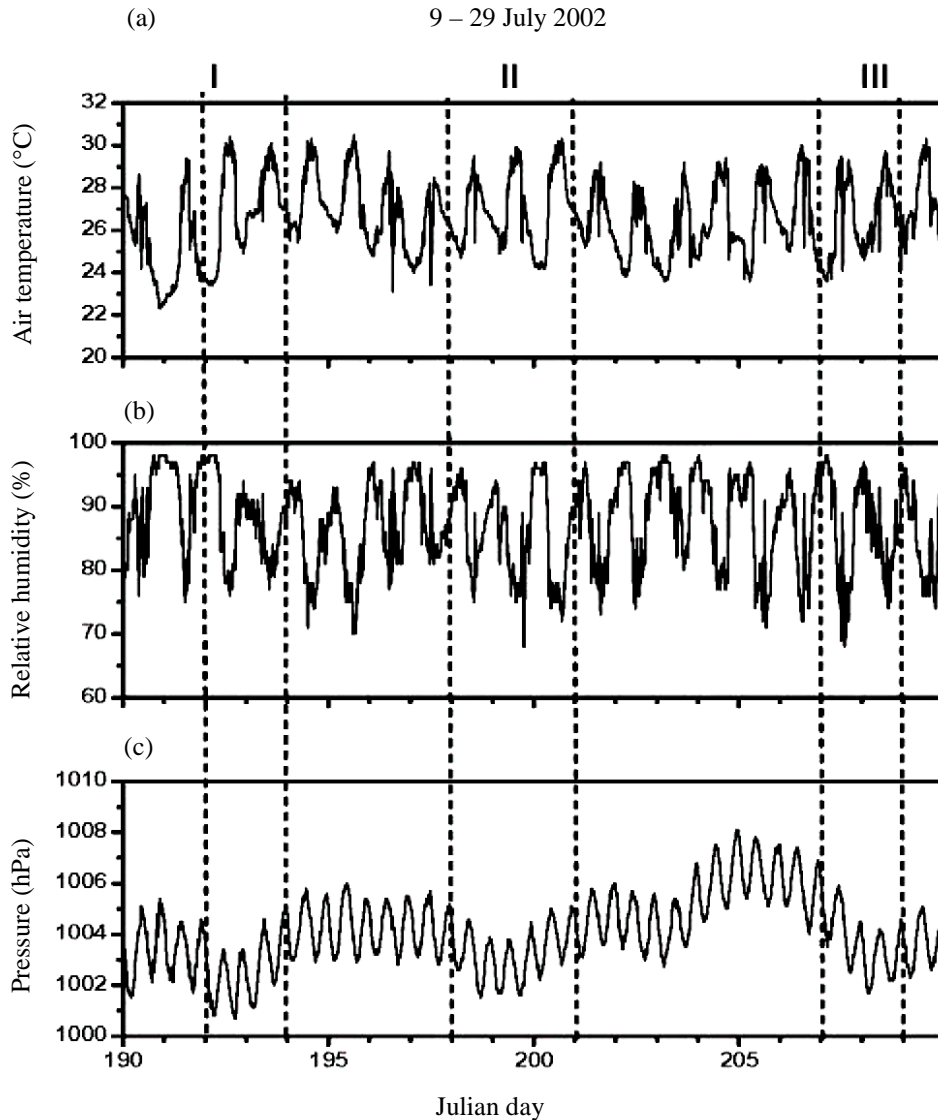


Figs. 2(a-c). Variation of surface parameters at Karvar (a) Air temperature ($^{\circ}\text{C}$), (b) Relative humidity (%) and (c) Surface pressure (hPa)

when the temperature too dipped to as low as 24.4°C . This could be attributed to the low pressure that leads the revival phase of monsoon after a prolonged break like condition in July 2002. During both the periods 2-5 (214-217 Julian Days) and 8-11 (220-223 Julian Day) August 2002 west coast received moderate to heavy precipitation. Most part of July 2002 (191-196 and 201-212 Julian Days) showed no significant variability that would initiate a convective process. The proportionate water vapour content contributing to the relative humidity during July 2002, as compared to the other two selected periods at Vijaydurg was also less.

Similar variations at Karvar (Fig. 2) is also seen and the three periods (I : 192-193, II : 198-201 and III : 213-

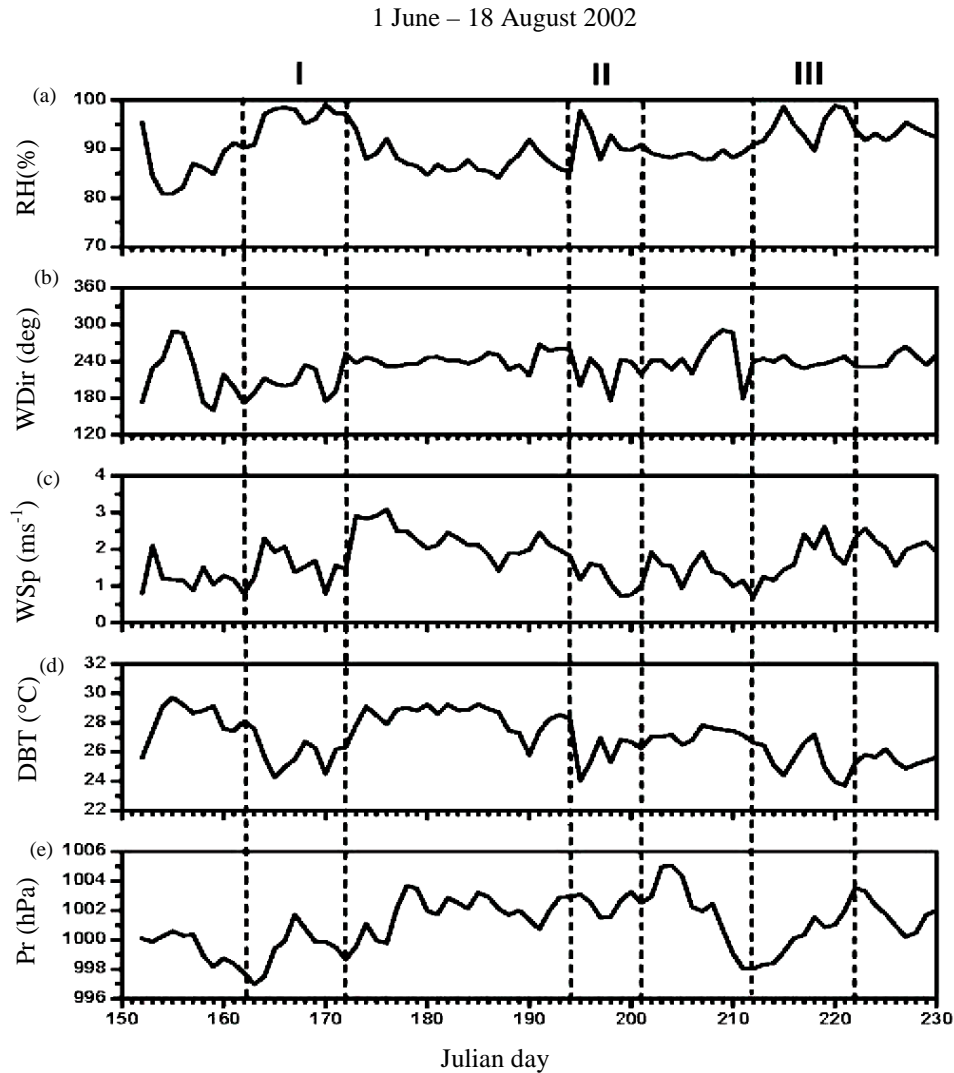
217 Julian Days) were delineated based on a considerable increase in the surface relative humidity [Fig. 2 (b)] and the surface pressure drop [Fig. 2 (c)]. During the III period the surface pressure and air temperature reached a minimum of 23°C and 1003 hPa respectively and the humidity level reaching a maximum of 98%. Satellite pictures too show low-level cumulus clouds during the III period (ARMEX weather summary). At Honavar, the surface pressure [Fig. 3 (c)] was almost always below 1006 hPa except during 204-208 Julian days when it touched a 2 hPa increase. The three delineated periods (I : 192-194, II : 198-201 and III : 207-209 Julian Days) showed considerable drop in pressure reaching a minimum between 1001-1002 hPa. The air temperature was also below 30°C during most of the days.



Figs. 3(a-c). Variation of surface parameters at Honavar (a) Air temperature (°C), (b) Relative humidity (%) and (c) Surface pressure (hPa)

Over Goa, precipitation with a maximum of ~620 mm was observed between 19 & 21 June and around 90 mm during 4 – 7 August 2002. Except for a peak of ~ 120 mm (16th July 2002) during July, the whole month was deprived of the usual SWM rainfall. Meteosat pictures also show convective cloud bands over Goa during 19 – 21 June and 4 – 7 August 2002, thus confirming the presence of convectively active atmosphere. Figs. 4 (a-e) show the variability of surface parameters *viz.*, relative humidity, wind direction, wind speed, dry bulb temperature and surface pressure over Goa from 1 June-18 August 2002 (152-230 Julian Days). The three chosen periods (I : 162-172, II : 194-201 and III : 202-222 Julian

Days) over Goa are the days that show significant rainfall activity during June, July and August respectively. The variations in the observed surface parameters do definitely reflect with regard to the initiation in convective processes leading to heavy precipitation. During the I period (11-21 June 2002) two phases of convective activity separated by ~48 hrs is noticed. One between 11-14 June 2002 and the other from 19-21 June 2002. Both of these periods show a significant drop in the surface pressure [Fig. 4 (e)] reaching to a minimum of 997 and 999 hPa respectively. The dry bulb temperature [Fig. 4 (d)] too shows two dips having minimum close to 24° C. Throughout this period the relative humidity [Fig. 4 (a)] was above 90% and it

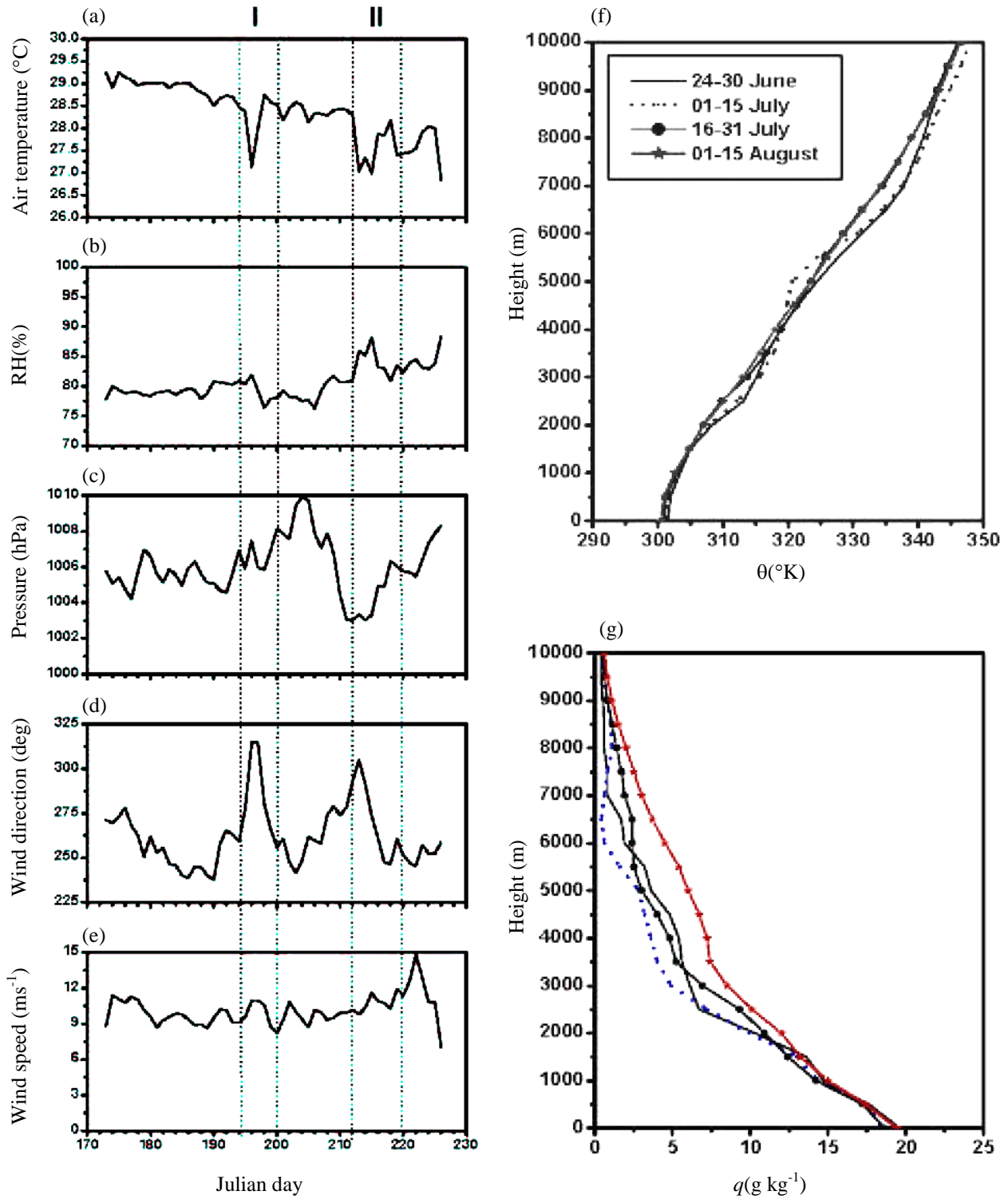


Figs. 4(a-e). Variation of surface parameters at Goa (a) Relative humidity (%), (b) Wind direction (deg), (c) Wind speed (ms^{-1}), (d) Dry Bulb temperature ($^{\circ}\text{C}$) and (e) Surface pressure (hPa)

neared 98% during both the phases of active convection during period I. After this period for almost 22 Julian Days the relative humidity on an average dipped 13-14 %, to later increase dramatically (13 %) evoking the II period (13-20 July 2002). Even though there was an increase in relative humidity and a considerable dip in the dry bulb temperature (reaching a minimum of 24°C), the pressure drop was comparatively less (~ 1 hPa drop) than that seen in I and III periods. Low pressure that was observed during the III period extended for longer time (207-214 Julian Days) than the other two periods, wherein there was little or no change in the wind direction (South westerly flow). The prolonged break like condition during July

2002 (173-194 Julian Days) is well represented by the negligible variations observed in the surface parameters Figs. 4(a-e).

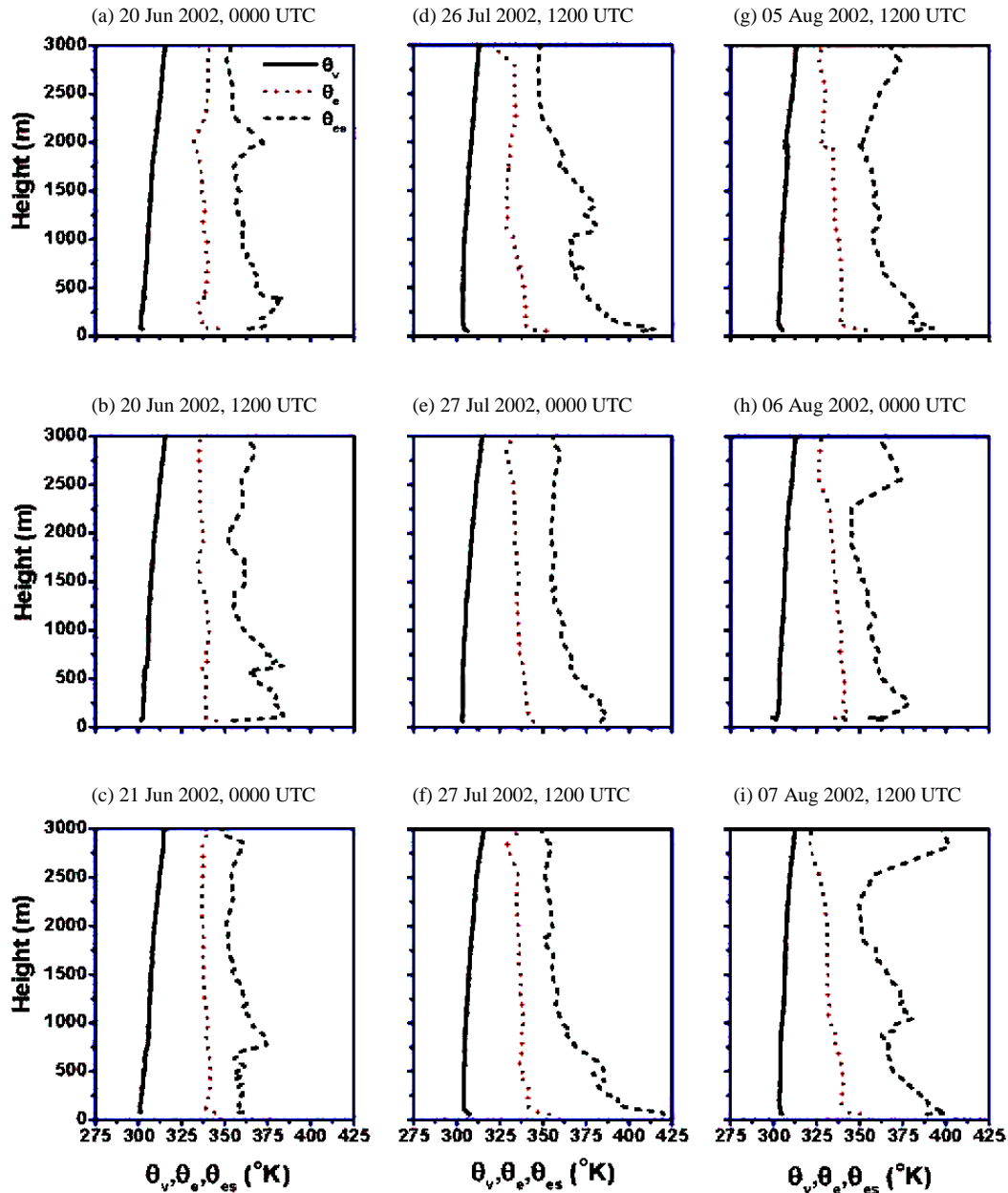
Figs. 5 (a-e) represents the surface variations of *viz.*, air-temperature, relative humidity, surface pressure, wind direction and speed respectively, observed onboard ORVSK during 173-226 Julian Days. During this period ORVSK cruised along the west-coast of India between $18 - 10^{\circ}\text{N}$. Observations onboard ORVSK indicate that sea-surface temperature never rose above 29°C during 1-11 July 2002. The air temperature [Fig. 5 (a)] dipped by almost 1.5°C during 13-17 July 2002 (194-198 Julian



Figs. 5(a-g). Variation of surface and mean upper air parameters over west coastal Arabian Sea onboard ORV Sagar Kanya (a) Air temperature (°C), (b) Relative humidity (%), (c) Surface pressure (hPa), (d) Wind direction (deg), (e) Wind speed (ms⁻¹), (f) Potential temperature (θ) and (g) Specific humidity (q)

Days). There was a decrease of ~ 10% in relative humidity [Fig. 5 (b)] and an increase of 2 hPa in the surface

pressure [Fig. 5 (c)]. The wind [Fig. 5 (d)] that was flowing in the south westerly direction changed into

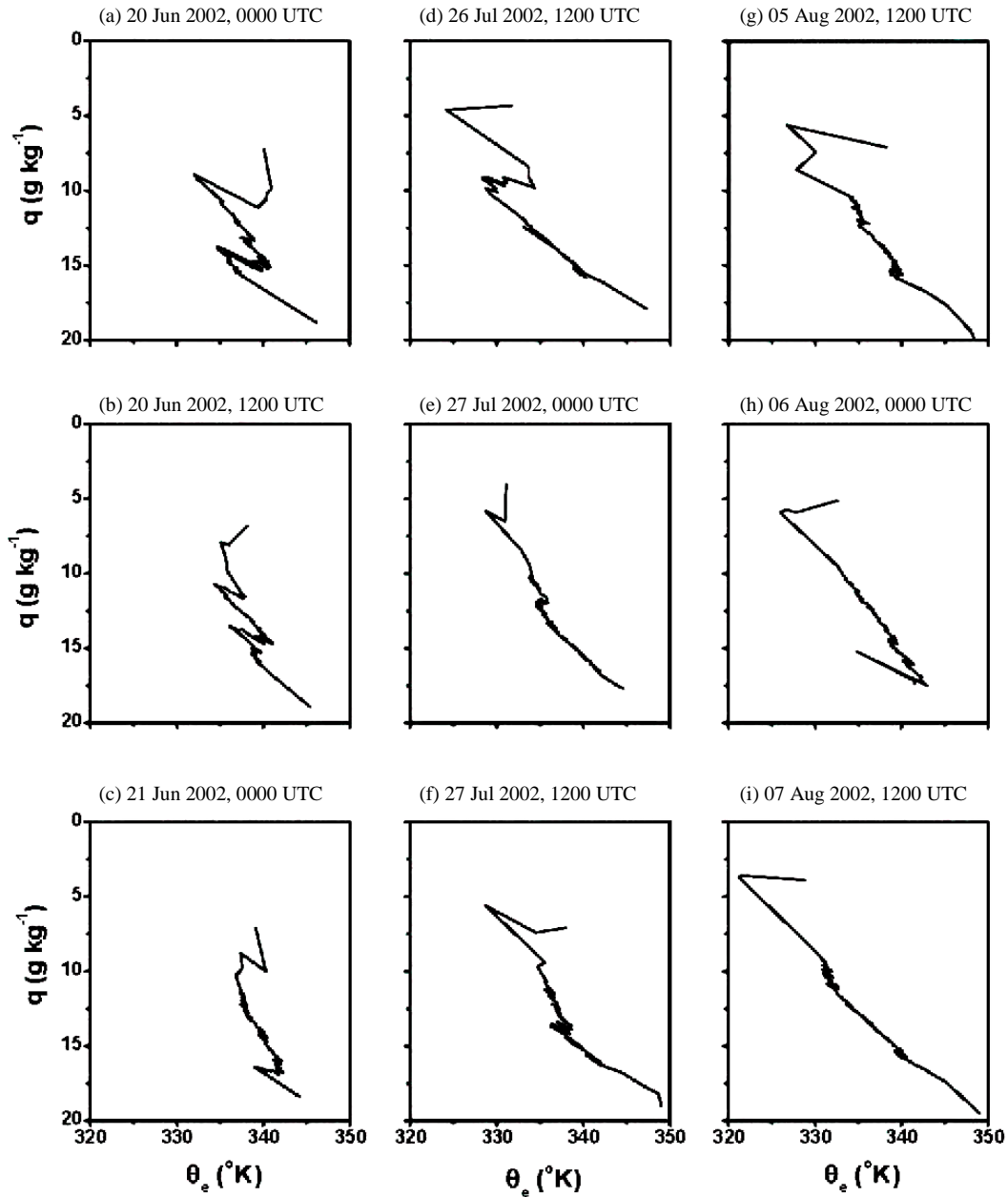


Figs. 6(a-i). Vertical profiles of conserved variables θ_v , θ_e and θ_{es} over Goa during Case-1 (a, b and c), Case-3 (d, e and f) and Case-2 (g, h and i). Case-1, Case-3 and Case-2 respectively depict three different periods of convective activity *viz.* 19-21 June, 4-7 August and 25-27 July 2002

north-north westerly flow restricting the zonal component of the SWM flow. The wind speeds [Fig. 5 (e)] were always well below 15 ms^{-1} over the west coastal Arabian Sea and on an average wind speeds ranged between $9\text{-}12 \text{ ms}^{-1}$.

On 1st August 2002 (213th Julian Day), a significant change in the wind direction is observed [Fig. 5 (d)], where the wind that was flowing in the north-north west

direction, was now in the south-west direction, indicating the revival of the monsoonal flow after an extended break like condition (194-212 Julian Days). During this extended break period the surface pressure rose to a remarkable high of $\sim 1010 \text{ hPa}$ on 23rd July 2002 (204th Julian Day). However, prior to the revival phase (in between 23rd July & 1st August 2002) that started on 1st August 2002, a surface pressure drop of almost 7 hPa [Fig. 5 (c)] was noticed along with a rise of 10% in



Figs. 7(a-i). $\theta_e - q$ profiles over Goa during Case-1 (a, b and c), Case-3 (d, e and f) and Case-2 (g, h and i). Case-1, Case-2 and Case-3 as described in Fig. 8

relative humidity over the Arabian Sea off the west coast of India.

4.2. *Upper air characteristics along the west coast of India*

The vertical profiles of temperature and relative humidity obtained on-board ORVSK during 24 June – 15 August 2002, was categorized into four periods *viz.*, 24-30

June, 1-15 July, 16-31 July and 1-15 August 2002. These profiles were used to compute θ and q during these four periods. The profiles of θ and q were averaged over these periods from surface up to 10 km and plotted. Figs. 5 (f&g) respectively, represents these mean profiles.

The average picture does not show any noticeable variability except for the period 1-15 July 2002. Close observation of average θ profiles [Fig. 5 (f)] reveals that

TABLE 1

Boundary layer height over Goa	
Days	Height (m)
26 June 2002, 0000 UTC	1010m
26 June 2002, 1200 UTC	831m
27 June 2002, 0600 UTC	1000m
27 June 2002, 1200 UTC	597m
5 July 2002, 0000 UTC	126m
6 July 2002, 0000 UTC	87m
9 July 2002, 0000 UTC	110m
10 July 2002, 0000 UTC	157m
3 August 2002, 0000 UTC	809m
3 August 2002, 1200 UTC	1365m
4 August 2002, 0000 UTC	686m
4 August 2002, 1200 UTC	975m

the MBLH was well below 500 m during this period and the profile depicted more or less a stable stratification, whereas for all the other periods the MBLH ranged from 750-2000 m. The mean specific humidity profile [Fig. 5 (g)] during 1-15 July 2002 however does show significant variation compared to the other three periods. At 4000 m from the surface, the specific humidity during this period is lesser by almost 3.5 g kg^{-1} from that observed during 1-15 August 2002. Such a continuous drying in the atmosphere inhibits the convective available potential energy and reflects in suppressing the convective activity.

Similar averages of vertical profiles were computed over Goa. No significant variability could be observed from the average θ profiles, except for the fact that the average during 1-15 July 2002 showed a stably stratified lower atmosphere, indicating inversion like condition. Based on the information obtained from ARMEX Weather Summary two periods of active convection with heavy precipitation and a period of suppressed convection with little or no rainfall was delineated over Goa. The active convection periods were 19-21 June 2002 (Case-1) and 4-7 August 2002 (Case-2) while the suppressed convection was observed from 25-27 July 2002 (Case-3). Fig. 6 shows the vertical variation of θ_v , θ_e , and θ_{es} during these three distinct periods. Figs. 6 (a-c) represents the profiles during Case-1, while Figs. 6 (d-f) and Figs. 6 (g-i) represents the profiles during Case-3 and Case-2 respectively. All of these three conserved variables θ_v , θ_e , and θ_{es} depict a highly stable atmosphere during Case-3, when the boundary layer height is restricted well below 250 m. On 20 June 2002 at 1200 UTC and 21 June 2002 0000 UTC the boundary layer height ranged between 750-1000 m (estimated using θ_{es}). Tables 1 and 2 depict the estimated boundary layer height (using θ_{es}) over Goa and

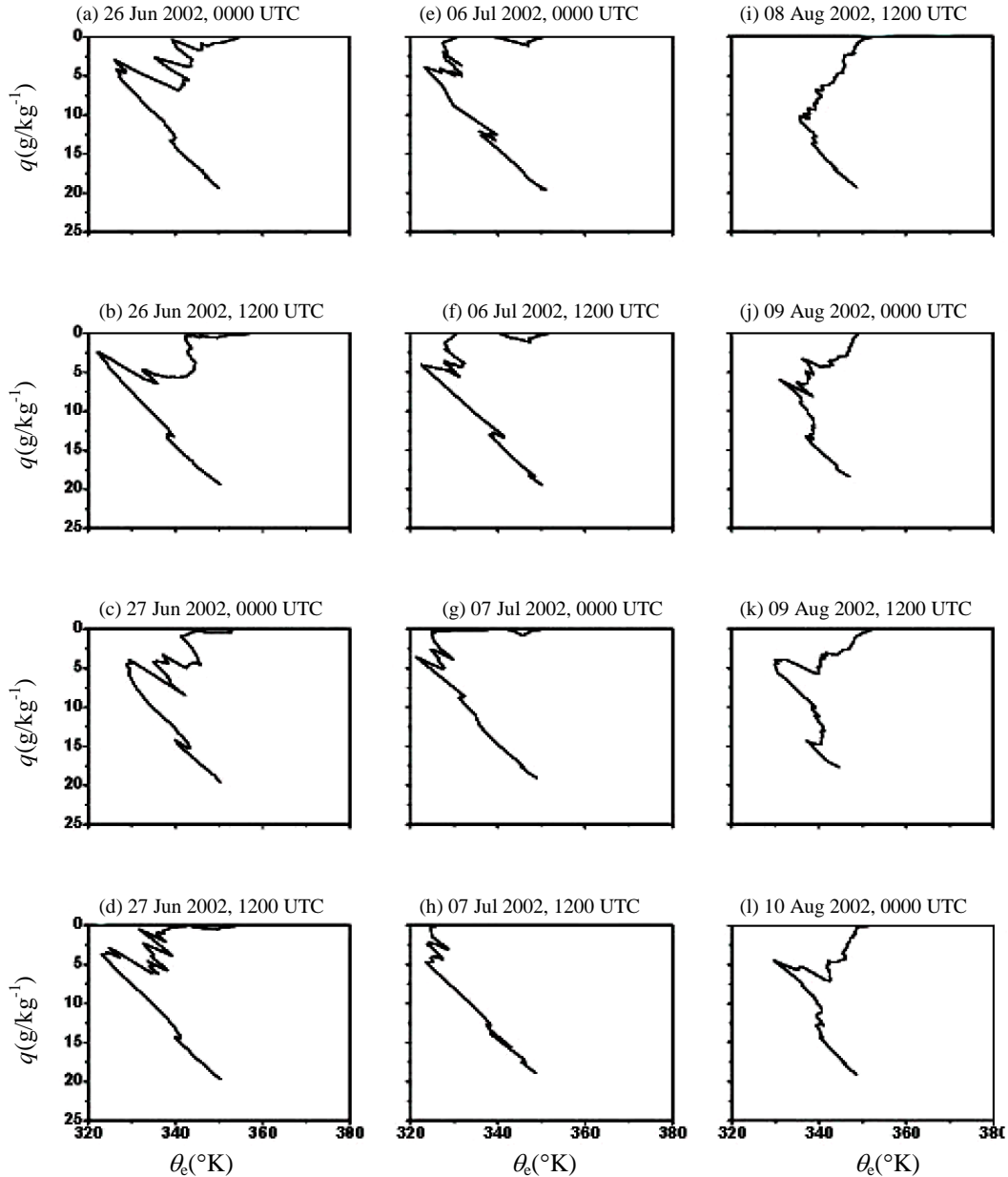
TABLE 2

Marine boundary layer height over Arabian sea off the west coast of India obtained onboard ORV Sagar Kanya	
Day, Time	Height (m)
5 July 2002, 1200 UTC	62
6 July 2002, 0000 UTC	45
6 July 2002, 1200 UTC	62
9 July 2002, 0000 UTC	62
9 July 2002, 1200 UTC	62
10 July 2002, 0000 UTC	62
10 July 2002, 1200 UTC	62
3 August 2002, 0000 UTC	975
3 August 2002, 1200 UTC	1162
4 August 2002, 0000 UTC	1545
4 August 2002, 1200 UTC	1161
8 August 2002, 1200 UTC	1260
9 August 2002, 0000 UTC	1355
9 August 2002, 1200 UTC	1652
10 August 2002, 0000 UTC	1068

over east coast Arabian Sea off the west coast of India respectively, during convectively active and suppressed conditions. The suppressed condition in July and the reduced coastal boundary layer heights correlate well with the prolonged break like condition that inhibited the growth in convective processes.

4.3. θ_e - q diagram

Figs. 7(a-i) represents the θ_e - q diagram during the three different convective periods over Goa as mentioned in the previous section, while Figs. 8(a-l) shows the θ_e - q diagram during three different convective episodes over west-coast Arabian Sea onboard ORVSK. The objective in plotting the θ_e - q diagram was to analyze the mixing in stratocumulus. The air above the convective boundary layer (CBL) is not coupled thermodynamically to the surface and is usually sinking with radiative cooling, and consequently decreasing θ_e . A sharp distinct kink found in θ_e - q diagram marks the mean CBL top. Hence the θ_e - q diagram could be used to approximate the height of the CBL. θ_{es} is found to be having largest value near this point. But at times the θ_e - q diagram shows a distinct double mixing line with another kink, found at some lower level which corresponds to the top of the moist conditionally unstable layer. This point is found to be near the place where θ_{es} value is minimum. This is the region of transition between two distinct mixing lines. Usually the shallower CBL tops are seen to have a single mixing line through the cloud and inversion layer with only one distinct kink at the mean CBL top. The distinct double structure [Figs. 7(a,b,d) and Figs. 8 (c,e,f,j,k) with a kink



Figs. 8(a-l). θ_e - q profiles over Arabian Sea off the west coast of India obtained onboard ORV Sagar Kanya during two active convection episodes *viz.*, (a-d) 26-27 June 2002, (i-l) 8-10 August 2002 and (e-h) a suppressed convection period 6-7 July 2002

near the θ_{es} minimum (top of the conditionally unstable cloud layer) and a second mixing line above through the inversion layer is a special feature of the deep CBL tops. This suggests that once the CBL reaches a certain depth a new physical process becomes important, and an obvious possibility is that the deepest clouds, which penetrate the inversion, start to precipitate, while populations of smaller clouds, that do not precipitate, continue to mix the conditionally unstable layer (Betts and Albrecht, 1987). Though the reason behind the occurrence of double mixing line is not understood but one of the possible

speculated mechanisms can be differential horizontal advection of boundary layers of different depths. Such double mixing line structure was rarely observed during July 2002.

4.4 Stability analysis

Stable boundary layer is characterized by the statically stable air with weaker, sporadic turbulence, as the statically stable air tends to suppress the turbulence. This is usually found during night time. However, even

during day time it can be found when the underlying surface is cooler than the air above. Static stability is a measure of the capability for buoyant convection. As the word 'static' means 'no motion'; hence this type of stability doesn't depend on wind. Figs. 8(a-l) shows the variation of the dry static energy with height over Goa during three different convective scenarios respectively during (I) 20-21 June, (II) 5-6; 9-10 July and (III) 3-4 August 2002. Air is statically unstable when less dense air (warmer and/or moisture) underlies more dense air. This instability causes convective circulations such as thermals that allow buoyant air to rise to the top of the unstable layer that tend to stabilize the atmosphere. Computations show that throughout the boundary layer dS/dz tends to be positive showing active convection, while dS/dz shows a negative gradient depicting suppressed convection.

5. Summary and conclusion

The observations carried out during ARMEX-I show the following :

(i) During July 2002 the boundary layer moisture convergence was inhibited as a result of reduced convective heating in the middle and upper troposphere, and the resulting lack of compensating upward motion. The dryness continues until the boundary layer can be moistened by advective processes.

(ii) The weak Somali Jet during July 2002 and the prevailing inversion condition could not initiate the advective processes. This could have resulted in a reduction of moisture convergence over the SWM region during July, a time when strong moisture convergence normally takes place.

(iii) The CVA is found to be useful in the study of the thermodynamic structure of the CBL. For Shallow CBLs (July 2002) during the suppressed convection period, a single mixing line is seen through the cloud and inversion layers. However, deeper CBLs during Case-1 and Case-2 at times show double mixing lines, possibly due to the precipitation-re-evaporation processes.

(iv) The structure of the boundary layer was also found to vary depending on the various factors that influence lower atmosphere and the general trend being a pronounced increase in the boundary layer height during an active convection process just before the heavy rainfall event. The diurnal variability of the BLH over Goa was more pronounced than that observed over the Arabian Sea off west coast of India. However the average BLH over the Arabian Sea off the west coast of India during the convectively active case was higher than that observed over Goa.

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