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Vertical structure of the lower atmosphere over the Arabian Sea and West Coast Station during weak phase of the Indian summer monsoon

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The height of the day time mixed layer, vertical structure of the atmospheric boundary layer (ABL) and its variation over the Arabian Sea (hereafter Sea) and the West Coast Station (Goa: 15°21' N, 73°51' E) during the weak phase of south-west monsoon (20-24 July 2002) have been calculated using Radiosonde, the surface meteorological data collected at 12 m above mean sea level onboard ORV Sagarkanya and at Goa during ARMEX-I. It is observed that the depth of mixed layer over Goa and offshore was about 1 km during the period, while the first 200 m was showing super adiabatic lapse rate over Goa but not over the Sea. The marine atmospheric boundary layer is found to be well-mixed with its height, progressively increasing from 750 m to 1000 m during 21-24 July 2002. The vertical profiles of virtual potential temperature show an inversion above 1 km, which was very steep over both the Sea and Goa. The relative humidity (RH) in the mixed layer (0-1 km AGL) was varying from 70 to 100% over the sea, whereas over Goa it was from 70 to 90 % during 20-24 July 2002. Above 2-3 km, RH decreases from 70% to 30% over the Arabian Sea and Goa on 24 July, indicating the presence of subsiding warm and relatively dry layer.

Keywords: Mixed layer, Virtual potential temperature, Relative humidity

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1 Introduction

The south-westerly monsoon flow first hits the west coast, resulting in significant change in thermodynamic structure of ABL over this region. Radiosondes from the ISMEX-1973 (Indo-Soviet Monsoon Experiment) data revealed that over a large portion of the Sea the moist layer was quite shallow[1]. Air masses are modified considerably through exchange processes in the PBL. The ARMEX (Arabian Sea Monsoon Experiment) was aimed towards understanding rainfall during monsoon on the west coast of India including the role of air-sea interaction in bringing very heavy precipitation at some stations in this region. Statistical analysis of the meteorological parameters shows that most of the time heavy precipitation events were due to deep convection in the Arabian Sea near the coast: ~100-200 km (ARMEX Science Plan (2001)). Study of Arabian Sea convection associated with intense rainfall events on the west coast of India includes study of genesis, maintenance and propagation of off-shore trough along the west coast of India, convective systems over eastern Arabian Sea, variation of air sea fluxes, vertical stability and wind shear in association with synoptic and mesoscale systems leading to very heavy rainfall events along the west coast[2]. Krishnamurthy[3] has reviewed the results of MONEX (Summer Monsoon Experiment) that includes the structure of the mixed layer, the day-night differences in the vertical motion profiles and the thermodynamic heat budget. Most of the earlier studies dealt with the western Arabian Sea only. It is therefore interesting to study the changes in the vertical profiles of temperature and humidity over the eastern Arabian Sea off the west coast and inland (at Goa) during the monsoon season.

2 Collection and utilization of meteorological data

Radiosonde data were collected by Indian Institute of Science (IISc), Bangalore over the Sea onboard ORV Sagarkanya during her cruise in ARMEX-I. On the coastal station radiosonde data were collected at 0000 and 1200 hrs GMT by Indian Navy at Goa. Data at 1200 hrs GMT were used to study the vertical structure of the atmosphere in relation to organization of convection and vertical fluxes of heat and water vapour over these stations. Data on wind speed and direction were not available on 23 July 2002 over Goa. The locations of various stations, over the Sea where the vessel was moored for radiosonde observations are: (15.70 °N, 72.22 °E), (15.74 °N, 72.35 °E), (15.36° N, 72.30 °E), (15.38 °N, 72.19 °E) and (15.38°N, 72.18 °E) on 20, 21, 22, 23 and 24 July 2002, respectively (Fig. 1). The location of the west

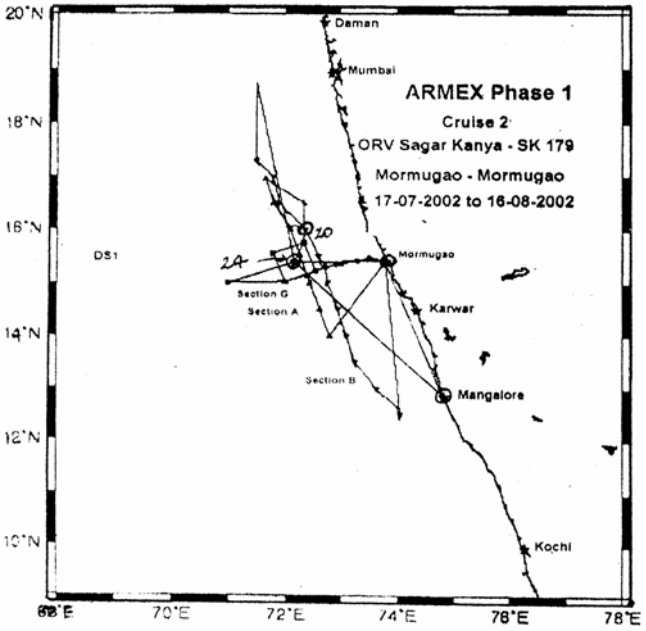

Fig. 1 — Location of experimental study area over Arabian Sea and West coast station.

coastal station is (15° 21' N, 73° 51' E) at Goa (Fig. 1). In this study, we used the data to compute the virtual potential temperature to estimate the height of the mixed layer over the Sea and Goa during the period of study (20-24 July 2002). Profiles of wind speed, direction, temperature and relative humidity were used to study the thermodynamic structure of the lower troposphere. Surface meteorological data (hourly averaged) collected onboard ORV Sagarkanya, sea surface temperature data (synoptic hours) over the Sea and air temperature at Goa (60 m MSL) are also utilized in this study.

3 Synoptic weather conditions during the study period

Weather over the Arabian Sea and Goa during July 2002 was characterized by scattered low/medium clouds over the sea, particularly close to the coast. The monsoon conditions over sea continued to be weak/moderate in July 2002 and hence no pronounced convective activity was observed in the eastern region of the Arabian Sea. The all-India monsoon rainfall for July 2002 was 49 % below its long term average with the largest deficits occurring in the western parts of India. No occasion of heavy rainfall event occurred where ORV Sagarkanya was located, nor an offshore

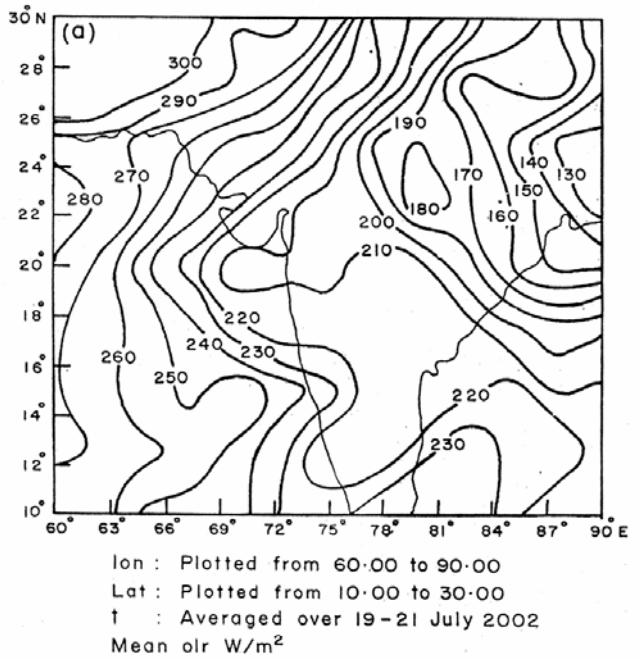

Fig. 2 — Variation of 3-day average of daily-mean OLR during the period (a) 19-21 and (b) 22-24 July 2002 [Data provided by the NOAA (National Oceanic and Atmospheric Administration) - CIRES Climate Diagnostics Center, Boulder, Colorado, Web site at http://www.cdc.noaa.gov/]

trough developed in its vicinity during most of July 2002.

Average outgoing long-wave radiation (OLR), shown in Fig. 2(a)-(b), shows relatively high values [Fig. 2(b)] during 22-24 July 2002 as compared to that during 19-21 July 2002 [Fig. 2(a)] over the eastern Arabian Sea and western India. The OLR over

the study area was about 250 W/m^2, suggesting suppressed convection and near the coast it is decreased to 240-230 W/m^2. The eastward spreading of high OLR (dry) regime was observed in Fig. 2. A weak trough over the sea off Kerala coast was noticed with light to moderate rainfall during this period along the west coast of India. On 21 July 2002 a weak trough of low was noticed off the west coast. The general flow in the Arabian Sea was south-westerly to westerly and the speed varied from less than 10 m/s to 20 m/s. The upper tropospheric easterlies at 150 hpa vary between 30 and 40 m/s from equator to 20 ºN. The total precipitable water in the south Arabian Sea vary from 35 to 40 mm while in the north Arabian Sea it varied from 40 to 50 mm.

Figures 3(a) and 3(b) show surface synoptic charts at 0300 hrs UTC for two days on 21 and 24 July 2002. As per India Meteorological Department (IMD)'s Indian Daily Weather Report (IDWR, 2002), the offshore trough well marked on 21 July, has become weak on 24 July 2002. On 24 July 2002 scattered low/medium clouds were observed over NE Arabian Sea and coastal region along the west coast of India. The offshore trough at sea level from Maharashtra coast to Kerala coast persisted during the period. Rising pressure from 17 to 24 July indicates unfavourable conditions for the development of convection[4]. An analysis of OLR, surface synoptic weather charts and the satellite photographs showed that the period of study was dominated by suppressed convection.

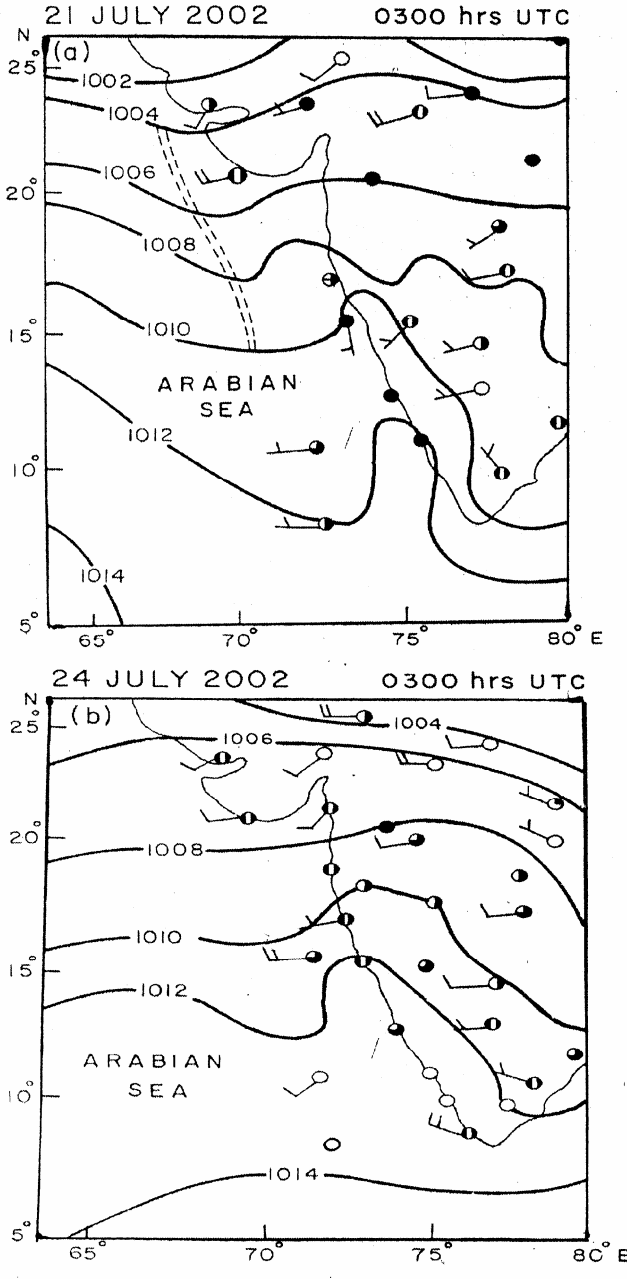

Fig. 3 — Surface synoptic charts at 0300 hrs UTC over Arabian Sea for (a) 21 and (b) 24 July 2002

4 Results and discussion

4.1 Profiles of wind, temperature and humidity off the coast and over Goa

The vertical structure of the boundary layer at 1200 hrs GMT over the Goa coast was analyzed using radiosonde data from ORV Sagarkanya and over Goa. Wind speed around 20 kt in the lower atmosphere (1.5 km AGL) was observed on 21 July 2002 over the Sagarkanya position. Figures 4 and 5 show the vertical profiles of different parameters as obtained from Sagarkanya and Goa soundings. It was observed that the depth of mixed layer over Goa and offshore was about 1 km during the period, while the first 200 m was showing super adiabatic lapse rate over Goa but not over offshore [Fig. 5(a)].

The profiles of wind indicated are shown in Figs 4(c) and 5(c). The vertical profiles of wind speed and direction over Sea and Goa showed similarity in the upper levels, whereas in the planetary boundary layer (PBL ≈ 2 km**)** over the Sea winds were observed in WSW-W and WSW-WNW sectors over Goa. Wind speed and direction were between SW-NW sectors in 2-7 km range above the boundary layer [Figs 4(c)-(d) and 5(c)-(d)]. Weakening of winds and significant fluctuations in RH in the range 40-90 % in the layer 2-5 km AGL indicated possible existence of clouds over the Sea.

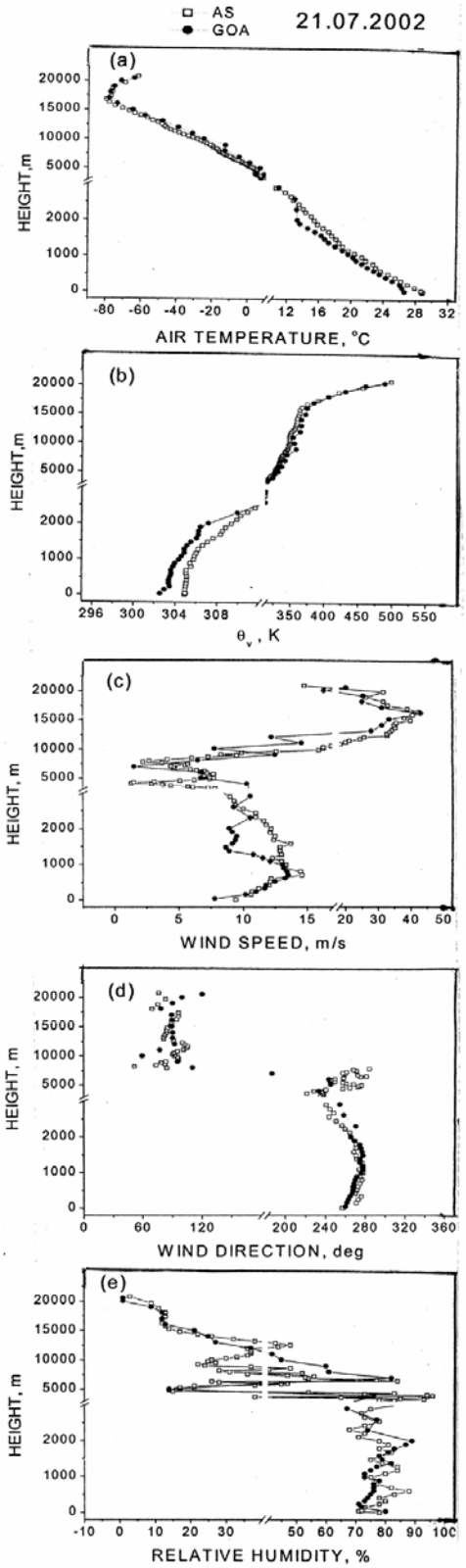

Fig. 4 — Profiles of (a) air temperature, (b) virtual potential temperature, (c) wind speed and (d) direction and (e) relative humidity over the Arabian Sea (AS) and Goa on July 21, 2002

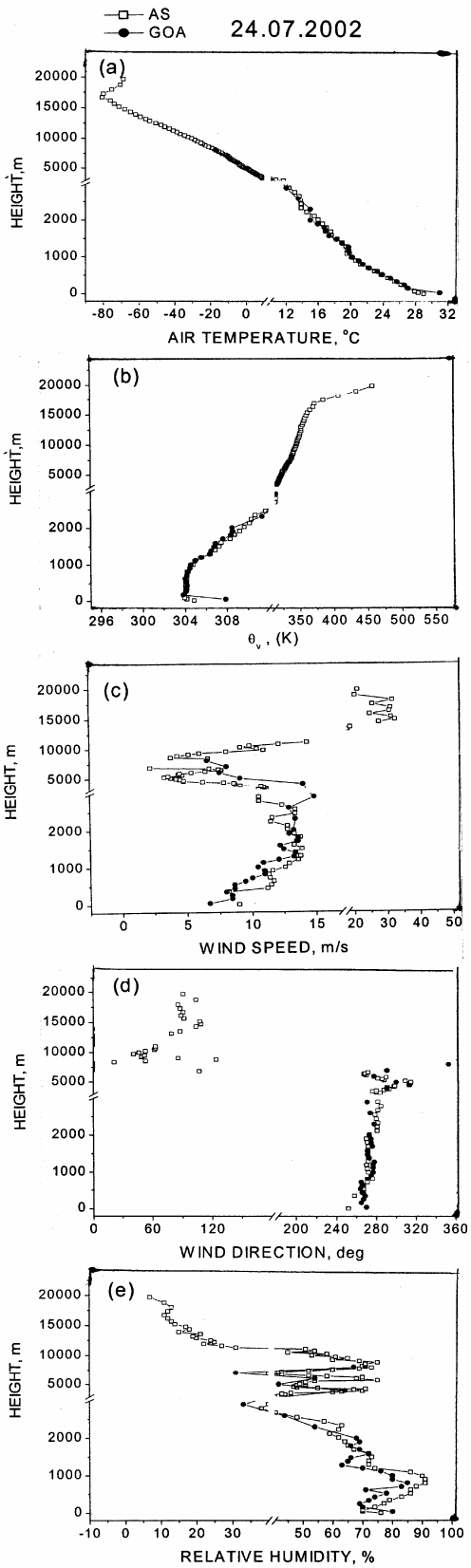

Fig. 5 — Same as Fig. 4 but for July 24, 2002

Table 1 — Mixed layer over the Arabian Sea and Goa

Date	Mixed layer height, m	
	Arabian Sea	Goa
20.07.05	Stable Atmosphere	1000
21.07.05	750	750
22.07.05	800	1000
23.07.05	900	1400
24.07.05	1250	1500

4.2 Mixed layer over the Sea and Goa

Table 1 shows the mixed layer heights over the Arabian Sea and Goa during the period 20-24 July 2002. The mixed layer depth is determined by following non-local parcel movement method[5]. It is seen from Table 1 that the atmospheric boundary layer height progressively increased from 750 to 1250 m during 21-24 July 2002 over the Arabian Sea. The depth of mixed layer over Goa was about 1000 m on 20 and 22 July 2002, 750 m on 21 July, 1400 m on 23 July 2002 and 1500 m on 24 July 2002, whereas over offshore areas the atmosphere was stable on 20 July 2002 with no mixed layer present [Figs 4(b) and 5(b)]. The marine atmospheric boundary layer was found to be well-mixed and its height progressively increased from 750 to 1250 m during the study period [(Figures 4(b) and 5(b)]**.** The vertical profiles of virtual potential temperature showed a stable layer above the mixed layer over both the Sea and Goa. Nevertheless the virtual potential temperature profiles on 21 July over Goa [Fig. 4(b)] showed that the atmosphere was stable in the boundary layer.

The relative humidity (RH) in the mixed layer (0-1 km AGL) was 70-100 % over the Sea whereas over Goa it was 70-90 % for 21 and 24 July [Figs 4(e) and 5(e)]. The dryness above 2 km layer is due to the advection of dry air from north and NW India during the period as revealed in the back trajectory analysis of NOAA HYSPLIT Model. There were significant fluctuations in RH in the range of 40-90 % with a weak stable layer above 2 km AGL over the Sea and land [Figs 4(e) and 5(e)].

4.3 Surface layer characteristics over the Sea and Goa

Distribution of wind speed (WS) and direction (WD), air temperature (AT), atmospheric pressure (*P*) and RH during the period 20-24 July 2002 over Sea

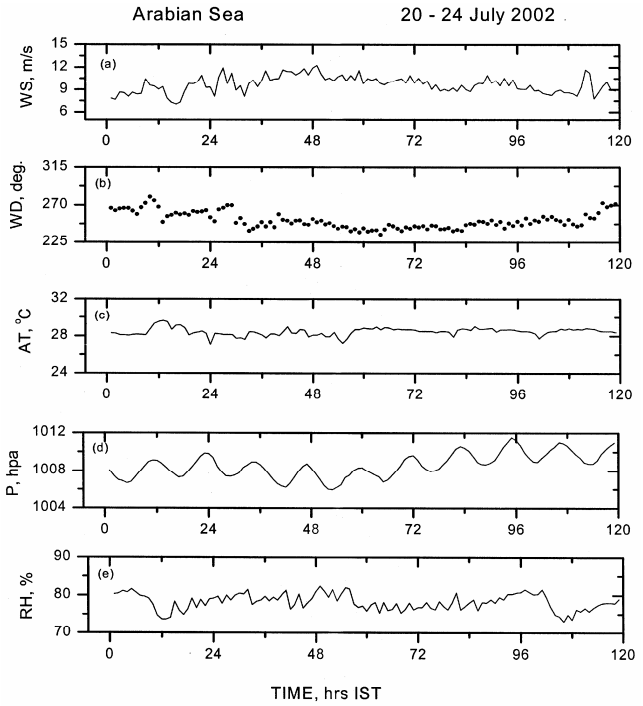

Fig. 6 — Distribution of (a) wind speed (WS), (b) direction (WD), (c) air temperature (AT), (d) atmospheric pressure (P) and (e) relative humidity (RH) during 20-24 July 2002 over Arabian Sea

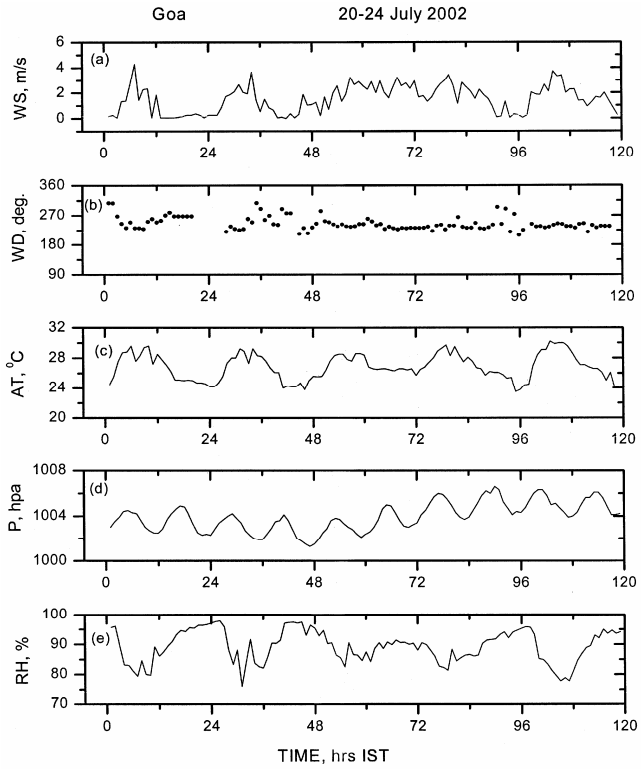

Fig. 7 — Same as Fig. 6 [(a)-(e)] but for land station (Goa)

and Goa, respectively are shown in Figs 6[(a)-(e)] and 7[(a)-(e)]. It is seen from Fig. 6(a) that the WS varied between 7 and 13 m/s with an average value of 10 m/s, whereas the WS was considerably weaker over Goa [Fig. 7(a)]. The WS is not uniform over Sea and Goa but appears to fluctuate frequently with amplitude of 1-4 m/s with change in pressure [Fig. 6(d)] and wind direction [Fig. 6(b)]. The WD [Fig. 6(b)] varied between 235° and 285° with its average value at 250° (i.e. west-south westerly) while in Goa the WD varied between 225° and 315° with its average value at 245° [Fig. 7(b)]. It is seen from Fig. 6(c) that AT over the Sea remained more or less constant at 28 °C with small fluctuations during night hours and this trend continued till the period of observations. The diurnal variation of AT is systematic during the period over Goa [Fig. 7(c)]. From Figs 6(d) and 7(d) it is noted that in general the mean sea level pressure (*P*) showed increasing trend and prominent semi-diurnal variation over Sea and Goa during 20-24 July 2002. The rising pressure from 20 to 24 July, 2002 suggests that this period was becoming unfavourable for the development of convection. The RH showed little variation (72-82 %) over Sea [Fig. 6(e)], whereas in Goa it showed diurnal variation during this period as shown in Fig. 7(e).

5 Conclusions

(i) The depth of mixed layer over the Arabian Sea varies from 750 m to 1000 m during 21-24 July, whereas over inland (Goa) it was from 1000 m to 1250 m during 20, 22 and 24 July. The increase over land may be due to frictional and diurnal heating processes.

(ii) Significant fluctuations in RH (30-70%) and weak winds above 2.5 km over the Sea and Goa were observed indicating mid-tropospheric subsidence and advection of relatively dry air at different levels from north and NW India.

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