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Characteristics of mixed layer over Arabian Sea during summer monsoon-2002

M. N. PATIL, B. S. MURTHY and S. SINHA

Indian Institute of Tropical Meteorology, Pune - 411 008, India

e mail : patil@tropmet.res.in

सार – अरब सागर मानसून प्रयोग (आरमेक्स) – 2002 के दौरान लिए गए प्रक्षेणों का उपयोग करते हुए समुद्री परिसीमा स्तर की विशेषता का अध्ययन किया गया है। रेडियो सौंदे प्रेक्षेणों का उपयोग करते हुए मिश्रित स्तर की उँचाइयों का आकलन किया गया है। इससे यह पता चला है कि मानसून के समय परिसीमा स्तर में दैनिक परिवर्तन कमजोर/अल्प होते है। मौसम की सिनॉप्टिक स्थितियों के अनुसार मिश्रित स्तर की उँचाई 200–1000 मी. के बीच होती है। औसत मिश्रित स्तर तापमान में वृद्धि के कारण संवहनी परिसीमा के स्तर में तीव्र वृद्धि देखी गई है।

ABSTRACT. Marine Boundary Layer feature has been studied using the observations collected during Arabian Sea Monsoon Experiment (ARMEX) – 2002. Mixed layer heights were estimated using radiosonde observations. It is observed that the boundary layer undergoes weak/small diurnal changes during monsoon conditions. The height of mixed layer varied from 200 – 1000 m depending on the synoptic weather conditions. Convective Boundary Layer is observed to grow rapidly with increase in mean mixed layer temperature.

Key words − ARMEX, Mixed layer, Virtual potential temperature, Elevated mixed layer.

1. Introduction

The vertical transport and diffusion of pollutants in the atmosphere depend on the height of convective boundary layer/mixed layer as this height gives a volume for the dispersion of pollutants. Passive quantities such as particles and gases are mixed nearly uniformly throughout the boundary layer by means of turbulence, which results partially from strong surface heating during the daytime hours. The mixed layer is capped by a temperature inversion, which impedes entrainment of dry air from above into that below, thereby limiting the height of mixing. Observations on the depth of marine boundary layer over the world ocean are sparse and may not be representative of climatological values. The marine atmospheric boundary layer is also a key parameter to understand the air-sea interactions and the modulation of convection. The sea surface temperature (SST) is affected by the atmospheric and oceanic mixed layer height and hence mixed layer studies are important in order to study the convective systems over oceans. When the mixed layer height is shallow, the heat fluxes are trapped in this shallow mixed layer and the SST can become warmer. Studies on the mixed layer over different oceanic region such as over Indian Ocean (Manghnani *et al.*, 2000), over Arabian sea (Parasnis and Morwal, 1993; Subrahamanyam and Radhika, 2003) and over Bay of Bengal (Bhatt *et al.*, 2000; 2001; Patil and Parasnis 2003) generated good amount of literature. In the present study, the mixed layer height is estimated using virtual potential temperature (θ_V) approach. The radiosonde observations collected during 1-15 August 2002 over the Arabian Sea were used. The spatial and temporal variations of mixed layer height were investigated and its dependency on surface wind speed and surface temperature are brought out.

2. Observations and weather conditions

During Intensive Observational Periods (IOP) of ARMEX, few additional observations were also taken. The available RS/RW observations are shown in Table 1. In the available data profile of meteorological parameters, about 12-13 data points are available in the lowest 1 km. A height resolution of 40-50 m in lower layer and 100-

TABLE 1

RS/RW observations available during ARMEX in August 2002 onboard ORV Sagarkanya

Date Aug 2002	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Hours of observations (UTC)	0028 0526 1112	0010 0532 1125 1723	0022 1121 1718	0023 0545 1118 1718	0012 0536 1151 1359	0017 1117	0017 1140	0031 1133	0036 1107	0013 1055 2031	0504 0923 1154 2024	0806	0039 1139 1532	0258 1541 2228	0532

TABLE 2

Day to day position of off shore trough and monsoon condition in Arabian Sea during 1-15 August 2002 at 0000 UTC

Date	Monsoon strength in Arabian Sea	Off shore trough	Pressure gradient between Trivandrum and Dahanu (hPa)
01 Aug	Weak/Moderate	Kerala-Karnataka	5.0
02 Aug	Moderate/Strong in south Weak/Moderate in north	Kerala-Karnataka	5.1
03 Aug	Moderate/Strong	Kerala-North Maharashtra	4.9
04 Aug	-	Karnataka-Konkan-Goa	4.8
05 Aug	Moderate/Strong	Karnataka	4.8
06 Aug	Moderate/Strong	Maharashtra-Coastal Karnataka	6.0
07 Aug	Moderate/Strong in north Moderate in south	Maharashtra – Coast of Kerala	7.0
08 Aug	Strong	Gujarat - Kerala	7.5
09 Aug	Strong	Gujarat - Kerala	7.5
10 Aug	Moderate/Strong	Off Karnataka	6.0
11 Aug	Moderate/Strong	Gujarat – North Karnataka coast	-
12 Aug	Moderate/Strong	Maharashtra-Kerala coast	6.7
13 Aug	-	-	7.5
14 Aug	Moderate	West coast	6.0
15 Aug	Moderate	-	5.0

150 m in higher layer was maintained to probe the boundary layer. The wind speed (ms^{-1}), temperature (°C) and humidity (%) along with pressure (hPa) were recorded. Using these observations, the vertical profiles of virtual potential temperature (θ_V), equivalent potential temperature (θ_e) and saturated equivalent potential temperature (θ_{es}) are estimated. The surface winds were strong (increased by 5-7 ms^{-1}) during the period of 10-15 August 2002 as compared to that of June and July. One of the heavy rainfall events along the west coast of India was recorded during 7-10 August 2002. Details on the observations and synoptic conditions are discussed elsewhere (Mohanty *et al*., 2002). During this observational period, off shore trough was persisted along the coasts of Maharashtra and Karnataka. On some occasions, this trough was extended up to Gujarat in the north to Kerala in the south. The general flow in the Arabian Sea was southwest to northwest during 1-3 August 2002. After this, the flow changed to southwest to west. The intensity of wind was 10-20 ms^{-1}. Low level Jet (LLJ) appeared in the north Arabian Sea on 7 August and was near the Konkan-Goa coast. Some times, LLJ reaches to north Maharashtra and Gujarat coast (on 12-13 August). Broken intense low/medium clouds with isolated convection (scattered to intense) were persisted along the coast of Konkan-Goa, Kerala, Karnataka, Maharashtra and Gujarat. The day-to-day intensity of monsoon along with position of off shore trough is given in Table 2. The monsoon activity became strong during 8-9 August with increase in pressure gradient (from near 5.0 to 7.5 hPa) between Trivandrum and Dahanu. During this period of strong monsoon activity, the offshore trough was also

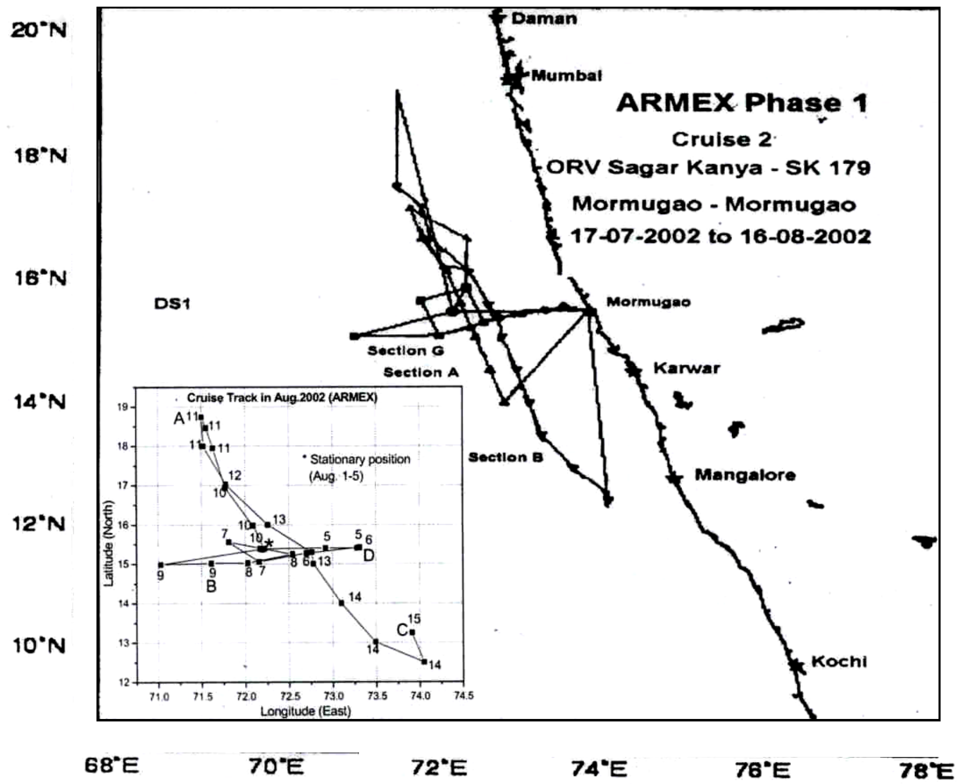


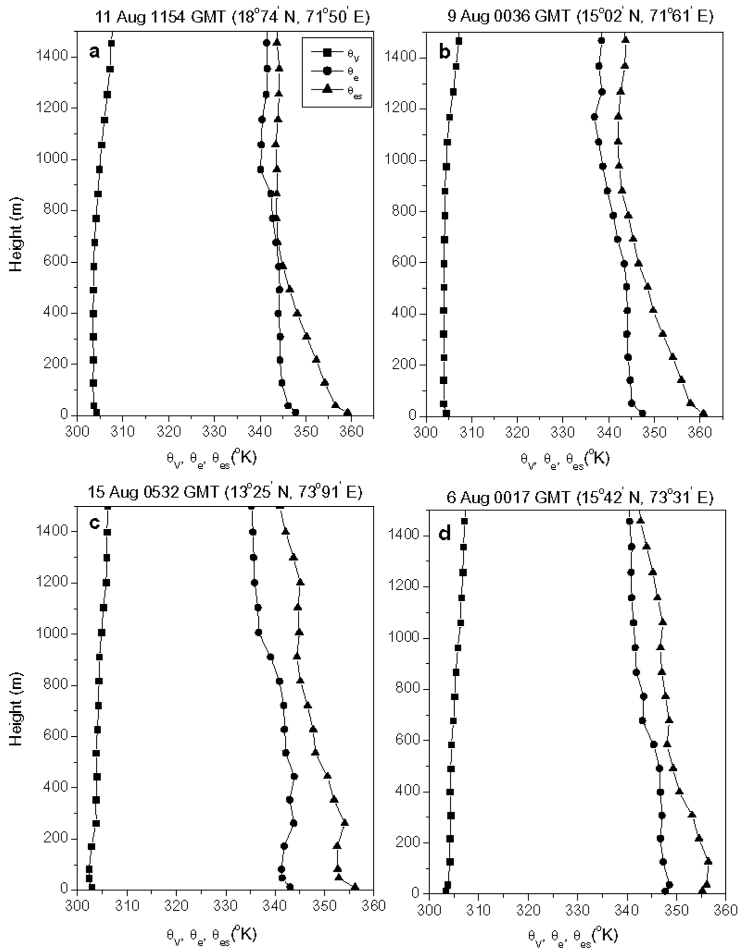
Fig. 1. Ship track of Sagarkanya SK-179 during 17 July 2002 – 16 August 2002. Inset picture shows the cruise position in August 2002. The number indicated against the ship position in date in August. Inset figure is generated from the available ship position in RS/RW sounding data. A, B, C and D region are marked in relation to show the spatial change in distribution of potential temperature as shown in Fig. 2

extended to Gujarat in northern direction to Kerala in southern direction.

3. Evolution of mixed layer

The cruise track in July to August 2002 is shown in Fig. 1. Day-to-day position of vessel in the month of August is shown in inset figure. The ship was stationary during 1-5 August and changing its position during 5-15 August. Figs. 2 (a-d) represents the profiles of θ_v, θ_e and θ_{es} for four different regions in the Arabian Sea. These regions are marked in Fig. 1 as A, B, C and D corresponding to higher latitudinal region, region away from the coast, lower latitudinal region and near coastal region respectively. The mixed layer height estimated from θ_v profile gives 820, 980, 180 and 600 m respectively in the region A, B, C, and D. The temperature changes within 1° K in the boundary layer despite the regions (A, B, C and D) are well away from each other. The difference of θ_e and θ_{es} at surface is less for the region D indicates that the lowest layer up to 400 m is humid. For the regions A, B and C, this difference is nearly constant and shows dry layer compared to that of D region. The narrowing of difference between θ_e and θ_{es} around at 600m indicates the presence of clouds.

Table 3 shows hour-to-hour variations in the mixed layer height as observed on 4-5 August 2002. It may be noted that 62 mm rainfall occurred on 4 August. The mixed layer height was in the range of 550-720 m in association with 1.4° C change in surface air temperature (26.8 - 28.2 °C). We examined the mixed layer potential temperature with change in mixed layer height. On an average mixed layer potential temperature stayed close to 300.5-302 °K (nearly constant) suggesting that the thermodynamic properties are conservative quantities. Thus, mean thermodynamic properties of the boundary layer remained nearly constant during monsoon conditions. Fig. 3 shows the day-to-day variation of mixed layer height as observed over Arabian Sea. The vessel was stationary at about (15° 38′N, 72° 18′E) during 1-5 August 2002 and was changing its position during 5-15 August. The mixed layer height was in the range of 200-1000 m



Figs. 2(a-d). Profile of Virtual potential temperature (θ_V), Equivalent potential temperature (θ_e) and Saturated equivalent potential temperature (θ_{es}) in different regions (a) A (b) B (c) C and (d) D of Arabia Sea. These regions are marked in Fig. 1

TABLE 3

Mixed Layer Height (MLH) as observed with the time of day

Date	Time Hrs (UTC)	MLH (m)	ML-θ (°K)	ML-θ_V (°K)	θ_S (°K)	T_S (°C)	W_S (ms^{-1})
04 Aug	0023	670	300.42	303.83	300.05	26.8	11.5
04 Aug	0545	680	300.81	304.24	300.65	27.4	-
04 Aug	1118	550	300.54	304.00	300.45	27.2	13.9
04 Aug	1718	720	301.61	305.21	301.35	28.1	11.1
05 Aug	0012	680	301.32	304.65	301.35	28.1	11.2
05 Aug	0536	720	301.62	305.15	301.45	28.2	12.5
05 Aug	1151	650	301.39	304.87	301.25	28.0	-
05 Aug	1359	710	301.41	304.78	301.05	27.8	11.8

(ML-θ is the mixed layer potential temperature, ML-θ_V is the mixed layer virtual potential temperature, θ_S is the surface potential temperature, T_S is the dry bulb temperature at surface and W_S is the surface wind speed)

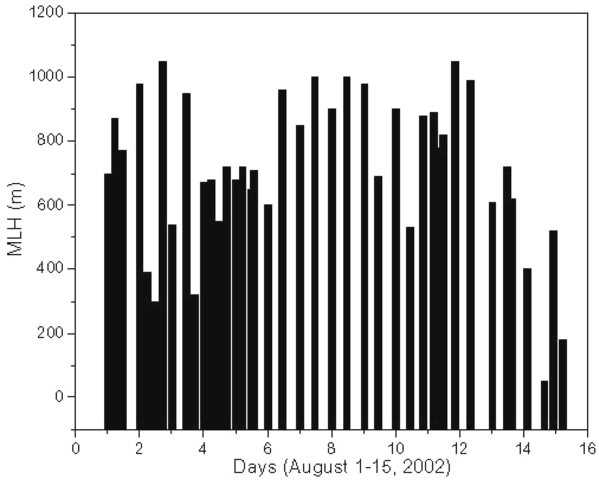
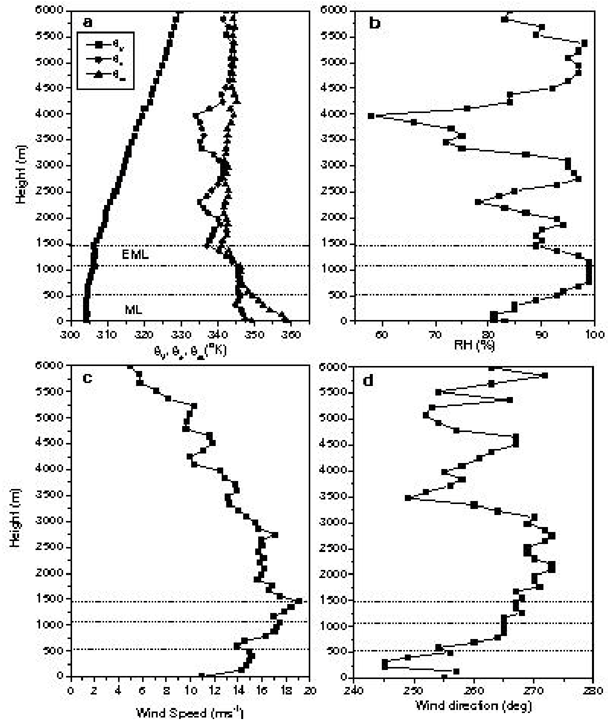


Fig. 3. Observed day-to-day variation of mixed layer height over Arabian Sea. The vessel was moored at about (15° 38′ N, 72° 18′ E) during 1-5 August 2002 and was changing its position during 5-15 August

TABLE 4

Rainfall recorded in August 2002 onboard ORV Sagarkanya

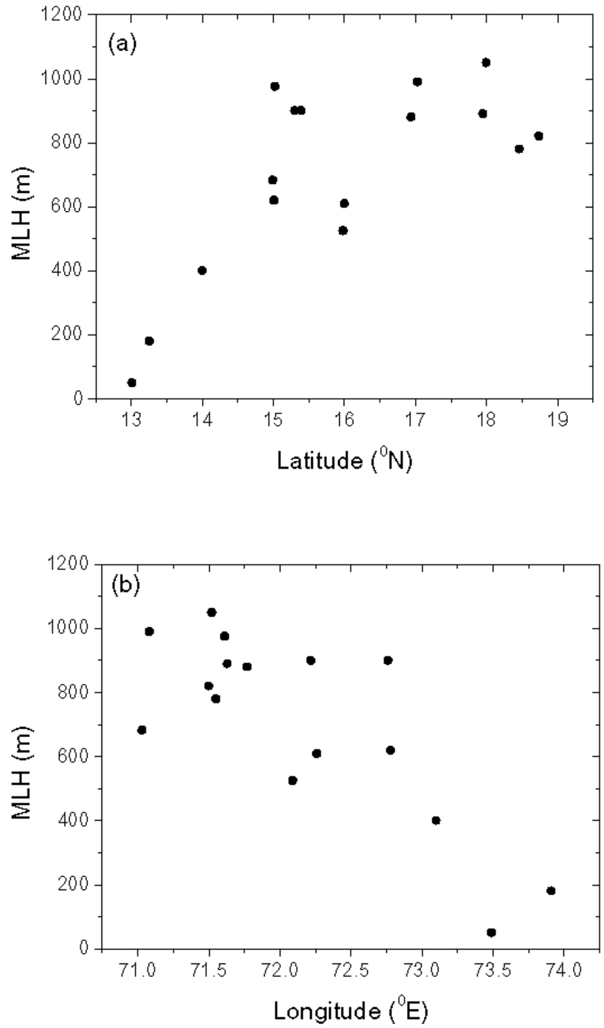
Date	Time (hours) of rainfall event (IST)	Rainfall (mm)
2 Aug	0600 to 1640	34.80
3 Aug	0300 to 2359	48.30
4 Aug	0000 to 1900	62.00
8 Aug	1050 to 1800	7.00
9 Aug	0140 to 0450	23.70
10 Aug	0150 to 0300	1.40
11 Aug	1000 to 1320	1.90



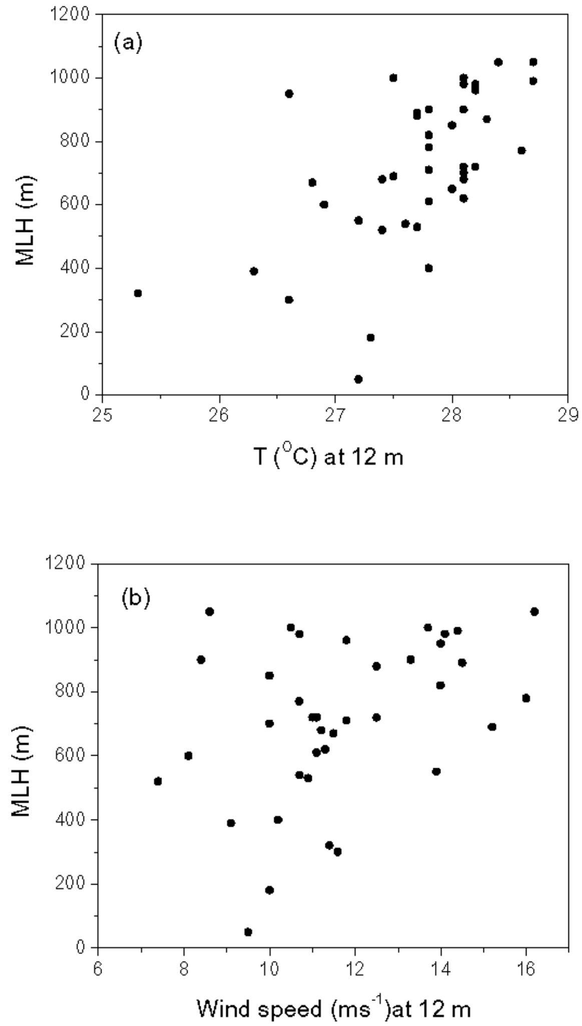
Figs. 4(a-d). Profile of (a) Virtual potential temperature (θ_V), Equivalent potential temperature (θ_e) and Saturated equivalent potential temperature (θ_{es}) (b) Relative Humidity (RH) (c) Wind speed and (d) Wind direction on 10 August 2002 (1055 hrs GMT) over Arabian Sea (15° 98′ N, 72° 09′ E). ML indicates the ground based mixed layer whereas EML indicates the elevated mixed layer

depending on the synoptic weather conditions and the location of ship. When the wind speed was strong (>12 ms^{-1}), the mixed layer attains 700-1100 m height, but at the moderate wind speed (6-12 ms^{-1}), a lot of variation in the mixed layer height was noticed. During 2-4 August, few observations show a remarkable decrease in mixed layer height. This is mainly due to the rainfall event occurred on these days. The observed rainfall is shown in Table 4.

In some cases, an elevated mixed layer was observed as shown in Fig. 4(a). The virtual potential temperature was constant up to the height of about 500 m. This layer is referred as a ground based mixed layer. Above this an increase in θ_v was observed for the next about 400-500 m, which is a stable layer. Above this stable layer, another mixed layer (constant θ_v region) of about 300-400 m width was noticed. This constant θ_v layer is referred as elevated mixed layer. The ground based mixed layer is associated with the upwards transport of convective fluxes whereas elevated mixed layer was associated with high wind speed and the decrease in humidity. Stable layer trapped between two mixed layers was associated with higher relative humidity (> 94%) as shown in Fig. 4(b). Top and bottom of the elevated mixed layer as well as stable layer was marked with negative wind gradient [Fig. 4(c)]. The top of the elevated mixed layer is marked with the influence of LLJ. The ground based mixed layer showed change in wind direction but above this there was a wind from uniform direction (265-270 deg) as shown in Fig. 4(d). On the top of elevated mixed layer, there was decrease in wind speed due to LLJ as noticed in Fig. 4(c). The difference between θ_e and θ_{es} [Fig. 4(a)] became very less in some of the layers above elevated mixed layer. Also humidity profile [Fig. 4(b)] suggested that another cloud layer appear in between 2800 & 5100 m



Figs. 5(a&b). Change in observed Mixed Layer Height (MLH) with (a) Latitude and (b) Longitude over the Arabian Sea



Figs. 6(a&b). Dependency of Mixed Layer Height (MLH) on (a) Temperature and (b) Surface wind speed

height as evidenced by relative humidity, which is greater than 95% at around 3 and 5 km. This implies that elevated mixed layer was a dry residual layer trapped between two clouds with nearly zero turbulence but neutrally buoyant. Such type of elevated mixed layer structure was observed during monsoon conditions over continental region of deep moist convective regions of monsoon trough over India by Vernekar *et al*. 1996.

4. Latitudinal variation of mixed layer height

During the second week of August, the vessel was changing its position from its moored position (15° 38′ N, 72° 18′ E) (Fig. 1). The observed changes in mixed layer height with latitude and longitude are shown in Figs. 5(a&b) respectively. Mixed layer height was found to increase with increase in latitude (in the region of 13° - 19° N) over the Arabian Sea. Thus the mixed layer height was greater in the northern part (17° - 19° N) and shallow in the southern part (13° - 14° N) of the Arabia Sea. Longitudinal variations of mixed layer height are shown in Fig. 5(b). The mixed layer height is greater in lower longitudes *i.e*., away from the coast while it is shallow in higher longitudinal area *i.e*., near the coastal region. Thus mixed layer height was higher in the regions away from the coast.

As shown in Table 4, two spell of rainfall occurred during 1-15 August in Arabian Sea. First spell was during 2-4 August (14.51 cm rainfall) and second spell was during 8-11 August (3.4 cm rainfall). Also the offshore trough was very active as shown in Table 2. These observations suggested active monsoon conditions over Arabian Sea. Bretherton and Wyant (1997) suggested that over subtropical oceans the shallow marine boundary layers were to exist in the up welling regions close to the coast and this marine boundary layer deepens with distance downwind as the boundary layer moves westward and equator ward. Transition from a well-mixed stratus/stratocumulus capped boundary layer into a decoupled trade-wind boundary layer. In the present study, we also observed higher mixed layer height away from the coast in Arabian Sea corroborating to the study of Bretherton and Wyant (1997). However since the single point observations on moving ship will not give a complete picture on this result. Simultaneous observations at coastal platform and away from seacoast (deep sea) are necessary to understand the dynamics of mixed layer over the region of coast and away from the coast (deep sea region).

The parameterization of mixed layer height with the surface meteorological parameters are important in order to access the height of mixed layer from the routine meteorological parameters such as surface wind speed, dry bulb temperature and humidity. The dependency of mixed layer height on surface temperature and surface wind is shown in Figs. 6 (a&b). The mixed layer height was increased linearly with increase in surface temperature. As shown in Fig. 6(b), for the surface wind speed less than 12 ms^{-1}, mixed layer height showed wide fluctuation ranging from 50 m to 1100 m. The mixed layer height was always greater than 600 m for strong winds (>13 ms^{-1}). Thus strong wind was associated with the higher mixed layer height. It suggests that, mixed layer attains greater height when surface temperature is high and surface wind is strong. Thus the boundary layer processes associated with the fluxes of heat and momentum plays an important role in the dynamics of mixed layer.

5. Summary

Analysis of the radiosonde observations collected during the Arabian Sea Monsoon Experiment – 2002 suggests that :

(*i*) The marine boundary layer over the Arabian Sea undergoes weak/small diurnal changes during the monsoon conditions. The height of the mixed layer varied from 200 – 1000 m depending on the synoptic weather conditions.

(*ii*) An elevated mixed layer was noticed above the low level clouds (high moisture-stable layer). Above this elevated mixed layer, decrease in wind speed was observed. The top of the elevated mixed layer was marked with the influence of LLJ.

(*iii*) Surface Temperature and surface wind speed play an important role in determining the mixed layer height. The mixed layer height increases with increase in surface temperature as well as surface wind.

(*iv*) The mixed layer height was shallow in the southern Indian coast of Arabian Sea and it increased towards the northern coast.

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