

Vertical structure of the planetary boundary layer in the west Indian Ocean during the Indian summer monsoon as revealed by ISMEX data

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ABSTRACT. During the Indo-Soviet Monsoon Experiment (ISMEX) 1973, closely spaced aerological measurements were obtained in the west Indian Ocean and the Arabian Sea. Based on these observations a study of the thermodynamical and kinematic structure of the atmospheric planetary boundary layer in this region is made. Under undisturbed weather conditions the planetary boundary layer is mainly divided into two sub-layers—the neutral stratified mixed layer and the cloud layer. In the region north of 10°N latitude over the Arabian Sea, a strong temperature inversion tops the boundary layer and shows a downward slope from the coast of India towards the west, thus reducing the planetary boundary layer in the western region to a mixed layer and a temperature inversion layer. In the extreme eastern region, strong convective mixing weakens the layered structure and leads to the destruction of the inversion.

A gradual increase of wind speed with height is observed in the sub-cloud layer in this region. A sharp maximum frequently occurs below 1200 m in the wind profiles in the region north of 7°N latitude over the Arabian Sea. The wind speed maximum occurs usually within the inversion layer in the western Arabian Sea and within the cloud layer in the central Arabian Sea, and is often associated with large values of wind shear at low levels.

1. Introduction

The vertical structure of the planetary boundary layer in the tropical Atlantic and Pacific Oceans has been extensively studied (Riehl *et al.* 1951; Malkus 1956, 1962; Roll 1965; Augstein *et al.* 1974; Brummer *et al.* 1974). Depending upon the vertical gradients of air temperature and specific humidity, the planetary boundary layer in these regions is sub-divided mainly into three layers. These are : (i) the surface layer, which extends from the sea surface to a height of about 100 m, has a superadiabatic temperature lapse rate and a decrease of specific humidity, (ii) the overlying neutral stratified mixed layer of about 600 m depth is characterised by an adiabatic temperature gradient and nearly vertical constancy of specific humidity and (iii) the cloud layer, which extends from the lifting condensation level to the base of the trade inversion above, has a temperature lapse slightly steeper than the moist adiabatic rate, and an upward weak decrease of specific humidity. The planetary boundary layer

is topped by the trade inversion which has a distinct increase of temperature with height and a steep decrease of specific humidity.

Very little is known about the vertical structure of the planetary boundary layer over the west Indian Ocean during the Indian southwest monsoon period. Radiosondes from ships and dropsondes from aircraft taken during the International Indian Ocean Expedition (IIOE) in the years 1963-65 provided, for the first time, some insight into the temperature and moisture stratification present in the lower troposphere over this region, particularly north of about 10°N in the Arabian Sea. The data revealed that at the equator and over a large portion of the Arabian Sea the moist layer was quite shallow. It also revealed the presence of a sharp temperature inversion in the layer 900-750 mb over the western and central regions of the Arabian Sea, with a dry and warm airmass prevailing above (Colon 1964; Bunker 1965; Sikka, *et al.* 1965; Desai 1968, 1969, 1970). A summary of all these studies is

given by Rao (1976). The IIOE data was, however, not adequate to delineate this different sub-layers of the planetary boundary layer in the region and to bring out their characteristic features.

The lower tropospheric circulation in this region of the globe differs significantly from that observed in other tropical oceans during the months of northern summer. With the onset of the summer monsoon over India and neighbourhood towards the end of May, a cool and moist airmass from the south Indian Ocean establishes itself in the lower troposphere above the warm waters of the Arabian Sea. A relatively warm and dry airmass of continental origin prevails above the moist monsoon current. While the pressure gradient and winds are weak in low latitudes of other tropical regions during this period, strongest winds occur over this area in the lower as well as in the upper troposphere. Occurrence of a low level jet (winds exceeding 50 kt) off Somalia and its further extension northeastwards across the Arabian Sea in the layer 1.0–2.0 km with associated strong vertical wind shears, is another feature which has no parallel elsewhere.

A detailed quantitative investigations of the time and space variations of the vertical distribution of temperature, humidity and wind velocity, as well as the fluxes of sensible and latent heat and momentum would help in the development of parameterization schemes and theoretical models of the boundary layer for this region. While estimates of the vertical energy transports at the air-sea interface have been reported by Ramage *et al.* (1972) based on the IIOE data and by Pant (1977) based on the ISMEX data, this study concentrates on the description of the vertical thermodynamical and kinematic structure of the planetary boundary layer in the west Indian Ocean during the Indian summer monsoon as revealed by the Indo-Soviet Monsoon Experiment (ISMEX) data collected during the months of June and July 1973.

2. Data

In the year 1973, intensive aerological measurements were carried out over the west Indian Ocean by four Russian research vessels *Priliv*, *Shokalsky*, *Voeikov* and *Okean* from 19 May to 8 July. This study utilises the radiosonde and radar wind observations taken on board the ships during the period 4 June to 8 July. From 4 to 25 June *Priliv* and *Shokalsky* made zonal cruises along 16°N and 11°N latitude respectively in the

Arabian Sea from the west coast of India upto the Arabian coast. During the same period *Voeikov* and *Okean* made meridional cruises roughly along 50°E and 58°E in the south Indian Ocean from the equator to 15°S. All the four ships remained practically stationary from 27 June to 2 July at their respective anchored positions near 18°0'N 67°0'E; 10°0'N, 60°0'E; 00°1'N, 50°0'E; and 00°1'N, 60°0'E. From 5 to 8 July *Priliv* and *Shokalsky* cruised along 11°5'N and *Voeikov* and *Okean* along 8°5'N from 60°E upto the west coast of India. Low level radiosonde and radar wind observations were taken at 6 to 12 hourly interval. These observations are available at locations about 1° apart along the zonal sections and about 2° to 3° apart along the meridional sections of the ships (Fig. 1). Since, the observations vary both in time and space, interpretation of data, therefore, implies a certain degree of steadiness in the flow within the layer considered for study. Very few observations are, however, available below 100 m height; therefore, a discussion of the surface boundary layer is not included in this study.

3. Synoptic situation

The period from 4 June to 8 July 1973 was characterised by a well developed southeasterly flow in the lower levels in the south Indian Ocean and a steady (in direction) southwesterly flow in the Arabian Sea. Depending upon the large scale weather conditions prevailing over the region, the period of study may be sub-divided into two periods. The first period (comprised of two sub-periods, *i.e.*, 4 to 16 June and 3 to 8 July) was characterised by a strong wind flow in the layer below 1500 m as compared to the second period (18 to 26 June) when the flow in this layer was relatively weak. The period from 27 June to 2 July may be considered a period of transition from a relatively weak flow to a strong flow over the region. During the first period, strong convective activity with rain showers was observed in the extreme eastern region of the Arabian Sea and in the vicinity of the equatorial trough in the south Indian Ocean. In the central region of the Arabian Sea and to the south of the equatorial trough, the ships observed 2-4 okta of Cumulus clouds with no rain showers. The western region of the Arabian Sea was nearly free from convective clouds. During the second period convective activity over the region was nearly absent. Western Arabian Sea remained completely free from convective clouds

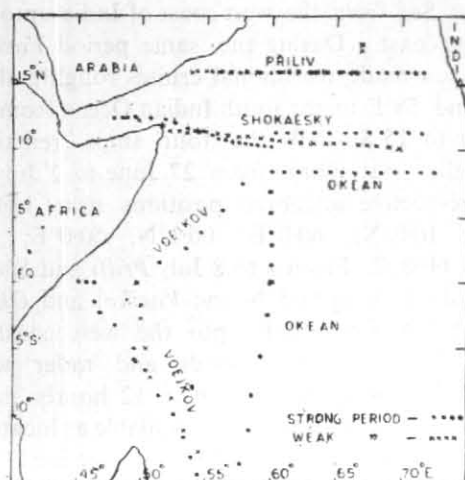
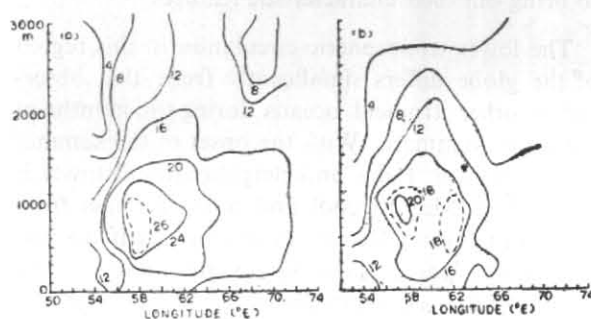
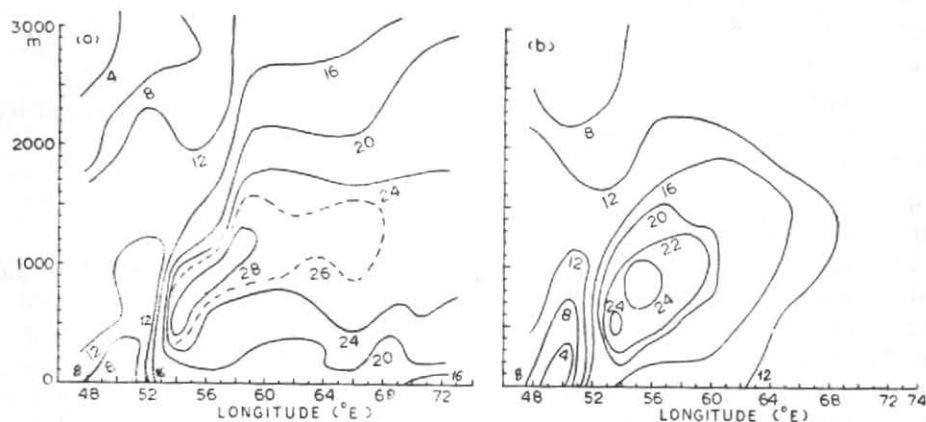


Fig. 1. Location of Russian research vessels during ISMEX 1973



(a) Strong period (10-16 June 1973) (b) Weak period (22-26 June 1973)

Fig. 2. Vertical distribution of wind speeds (mps) along 16°N



(a) Strong period—6-11 June and 5-8 July 1973 (b) Weak period—18-25 June 1973

Fig. 3. Vertical distribution of wind speeds (mps) along 11°N latitude

in this period also. Figs. 2 and 3 illustrate the cross-sections of wind speeds along 16°N and 11°N for the first and second period respectively. Similar cross-sections of wind speed were also prepared along 50°E in the south Indian Ocean for the two periods (not presented).

4. Sub-divisions of the planetary boundary layer and their characteristic features

Profiles of air temperature, specific humidity and virtual potential temperature were constructed from the sea surface to a height of 3.0 km a.s.l. Characteristic discontinuities were observed in the vertical gradients of these elements in the individual profiles under undisturbed conditions. Based on these discontinuities and in accordance

with the classification used in the literature, the planetary boundary layer in this region is mainly sub-divided into two layers, viz., (i) the neutral stratified mixed layer, and (ii) the cloud layer. The cloud layer is not everywhere topped by an inversion in this region, but either an isothermal layer or a stable layer, with lapse rate less than 0.4°C per 100 m tops this layer.

The neutral stratified mixed layer—This layer is characterised by a nearly constant distribution of virtual potential temperature (θ_v) with height. The lapse rate of temperature is close to the dry adiabatic rate and the specific humidity shows a strong upward decrease in this layer.

The cloud layer—The cloud layer extends from the top of the lifting condensation level (LCL)

(the LCL generally coincides with the top of the mixed layer at most of the locations in undisturbed situations) to the base of inversion or stable layer above. This layer is characterised by a small increase of θ_v with height. The lapse rate of temperature is close to the moist adiabatic rate and the specific humidity shows a weaker decrease with height as compared to that in the mixed layer. One of the most striking features brought out by these profiles is that the cloud layer is very shallow in the region north of 10°N and west of 60°E over the Arabian Sea during both the strong and weak periods.

5. Vertical distribution of temperature and specific humidity and stability conditions in the different sub-layers

From the vertical profiles of air temperature (T) and specific humidity (q) constructed for different locations in the region (Figs. 4 to 6), it is found that under undisturbed conditions the lapse rate of T in the mixed layer is generally close to the dry-adiabatic rate during both the strong and weak periods. Super adiabatic rates are, however, found to occur in this layer in some of the profiles in the western and central regions of the Arabian Sea particularly during the weak period. The specific humidity shows a strong upward decrease in the mixed layer in both the periods. The vertical gradients of q are found to be more marked during the weak period than during the strong period.

The cloud layer is nearly absent in the region north of 10°N and west of 60°E over the Arabian Sea in both the periods. The lapse rate of T in this layer in the region to the east of 60°E and north of 10°N varies with in the range of 0.55 — 0.75°C per 100 m. To the south of 10°N the lapse rate of temperature in this layer is comparatively less and varies from 0.45 to 0.60°C per 100 m.

Average lapse rates (per 100 m) of T , q and θ_v in the mixed and cloud layers are worked out for each 3-4 degree interval along 16°N and 11°N over the Arabian Sea for both the strong and weak flow periods and are presented in Table 1. Average lapse rates of q and θ_v in the inversion layers present at 16°N and 11°N have also been presented for both the periods. The most significant difference between the two periods lies in the vertical moisture distribution in the mixed layer which in the weak period shows a comparatively steeper lapse than that of in the

strong period. This phenomenon may perhaps be attributed to the relatively weak dynamic turbulence in the surface layer during the weak flow which impeded the vertical humidity flux and led to moisture accumulation near the surface. Another noteworthy feature in the region is the small moisture lapse within the inversion layer in the central Arabian Sea where the moisture shows even an increase with height during the weak period. This feature differs markedly from that observed in other tropical oceans where the moisture sharply decreases with height above the inversion base.

Some insight into the static stability and convective stability of the different sub-layers of the planetary boundary layer can be had from the vertical distributions of the virtual potential temperature, θ_v and the equivalent potential temperature, θ_e in these layers. Within the mixed layer θ_v tends to be nearly constant but θ_e strongly decreases with height (Figs. 7 and 8). This makes the layer both conditionally and convectively unstable. Within the cloud layer θ_v shows a weak increase and θ_e a lesser decrease with height as compared to that of in the mixed layer. The distribution is weakly unstable. Under undisturbed conditions, θ_e shows a decrease upto the inversion base, but within the inversion the equivalent potential temperature strongly increases with height. Under disturbed situations, when cumulus convection becomes stronger, as observed in the extreme eastern region of the Arabian Sea and also in the vicinity of the equatorial trough during the strong period, the thermodynamical discontinuities in the boundary layer are considerably smoothed out. The minimum θ_e at the inversion base is less pronounced and it nearly vanishes in situations without inversion.

6. Variations in the depths of different sub-layers of the planetary boundary layer over the Arabian Sea

The sub-layers of the planetary boundary layer show a significant variation in their depths from one region to the other over the Arabian Sea particularly in the region to the north of 10°N . Over the south Arabian Sea, however, the variations are insignificant. Figs. 9 and 10 show the actual distribution of the different sub-layers at 16°N and 11°N respectively for both the strong and weak flow in the region. In the extreme western region

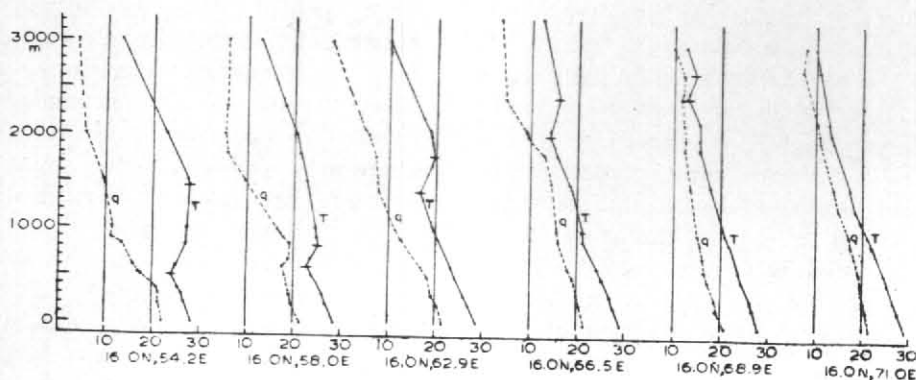


Fig. 4 (a). Profiles of air temperature ($^{\circ}\text{C}$) and specific humidity (g/kg) along 16°N —during strong period

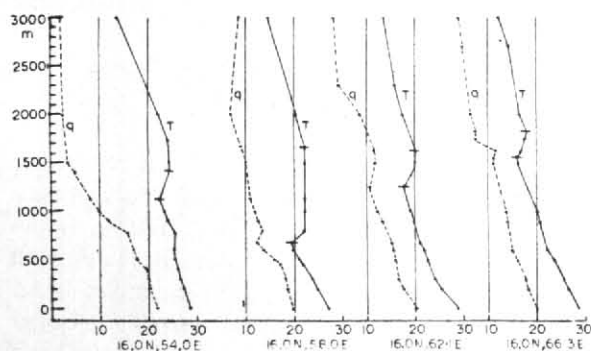


Fig. 4 (b). Profiles of air temperature ($^{\circ}\text{C}$) and specific humidity (g/kg) along 16°N —during weak period

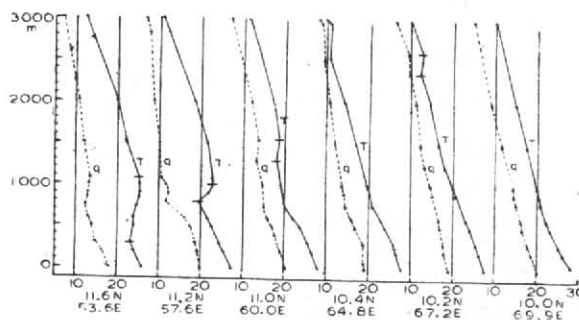


Fig. 5 (b). Profiles of air temperature ($^{\circ}\text{C}$) and specific humidity (g/kg) along 11°N —during weak period

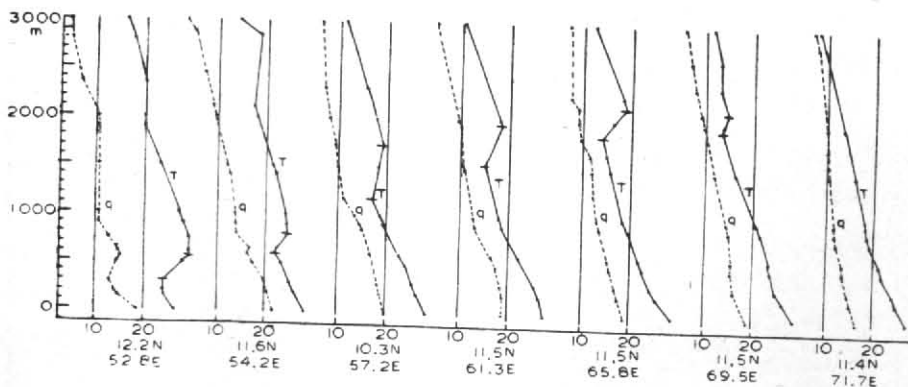


Fig. 5 (a). Profiles of air temperature ($^{\circ}\text{C}$) and specific humidity (g/kg) along 11°N —during strong period

of the Arabian Sea, the mixed layer is quite shallow (less than 200 m in depth) during both the periods. A gradual deepening of this layer occurs towards the east. The deepening is more marked in the strong flow than in weak flow period. Similar variations also occur in the depth of the cloud layer. To the west of about 60°E , a strong tempera-

ture inversion caps the mixed layer in both the periods, thus nearly completely eliminating the intervening cloud layer from this region. With the gradual lifting of the inversion base towards the east of 60°E , the cloud layer also deepens. In the extreme eastern region of the Arabian Sea, where the inversion is generally absent, the top of

TABLE 1
Some characteristics of the different sub-layers of the planetary boundary layer and of inversion layer in the Arabian Sea

Location				Mixed Layer			Cloud Layer				Inversion Layer		
Lat. (°N)	Long. (°E)	Ht of top (m)	Lapse rate (per 100 m)	Depth (m)	Lapse rate (per 100 m)	Ht of base (m)	Lapse rate (per 100 m)	Depth (m)	Lapse rate (per 100 m)	Ht of base (m)	Lapse rate (per 100 m)	Depth (m)	Lapse rate (per 100 m)
		T (°C)		q (g/kg)		θ_v (°A)		T (°C)		q (g/kg)		θ_v (°A)	
Strong period													
16	54	200	-0.90	-0.80	-0.05	Absent	-	-	Absent	500	-0.65	500	+1.55
16	58	550	-0.97	-0.60	-0.02	Absent	-	-	Absent	600	+0.13	600	+1.94
16	62	600	-0.98	-0.83	-0.14	-0.66	-0.78	+0.18	-0.66	1200	-0.08	1200	+1.92
16	66	750	-0.89	-0.63	-0.03	-0.62	-0.58	+0.26	-0.62	1600	-0.56	1600	+1.40
16	70	900	-0.75	-0.53	+0.10	-0.66	-0.57	+0.22	-0.66	-	Absent	-	-
11	54	500	-0.93	-0.85	-0.12	Absent	-	-	Absent	500	-0.87	500	+2.02
11	58	900	-0.95	-0.67	-0.06	Absent	-	-	Absent	1100	-0.30	1100	+1.50
11	62	950	-0.98	-0.65	-0.12	-0.62	-0.45	+0.22	-0.62	1600	-0.26	1600	+1.80
11	66	1000	-0.98	-0.58	-0.13	-0.56	-0.46	+0.27	-0.56	2000	-0.20	2000	+2.40
11	70	1000	-0.96	-0.55	-0.01	-0.56	-0.30	+0.30	-0.56	-	Absent	-	-
Weak period													
16	54	300	-0.93	-0.98	-0.14	-	-	-	-	500	-1.14	500	+1.74
16	58	600	-1.04	-1.00	-0.26	-	-	-	-	600	+0.87	600	+2.83
16	62	550	-1.03	-0.84	-0.23	-0.73	-0.60	+0.24	-0.73	1250	+0.41	1250	+2.25
16	66	600	-1.00	-0.76	-0.15	-0.70	-0.52	+0.19	-0.70	1300	-0.75	1300	+1.53
11	54	300	-0.93	-1.28	-0.15	-	-	-	-	300	+0.14	300	+2.20
11	58	700	-1.02	-0.94	-0.23	-	-	-	-	700	+0.42	700	+2.70
11	62	900	-0.98	-0.69	-0.14	-0.70	-0.45	+0.15	-0.70	1200	-0.08	1200	+1.50
11	66	700	-0.96	-0.62	-0.12	-0.62	-0.35	+0.32	-0.62	2100	-0.26	2100	+1.10
11	70	800	-1.00	-0.66	-0.13	-0.64	-0.45	+0.35	-0.64	-	Absent	-	-

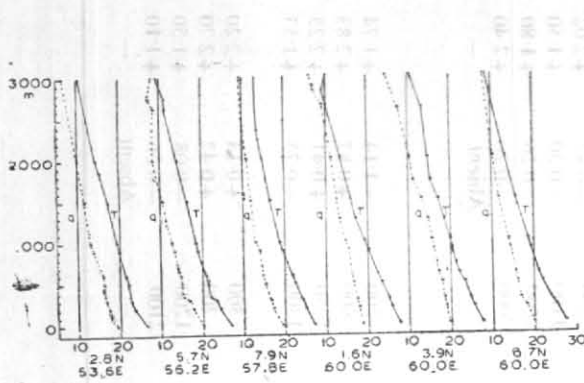


Fig. 6 (a) Profiles of temperature ($^{\circ}\text{C}$) and specific humidity (g/kg) over south Arabian Sea—during strong period (3-5 July)

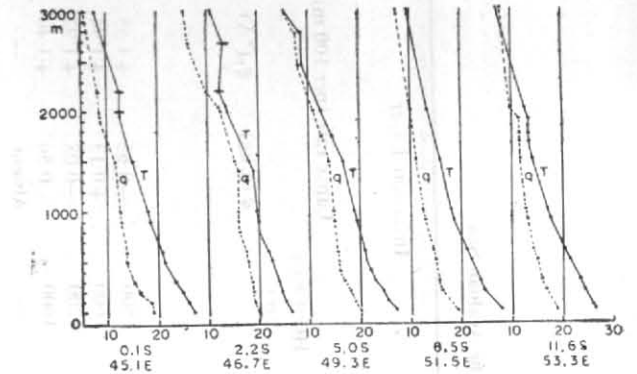


Fig. 6 (b) Profiles of temperature ($^{\circ}\text{C}$) and specific humidity (g/kg) over west Indian Ocean—during strong period (8-12 June)

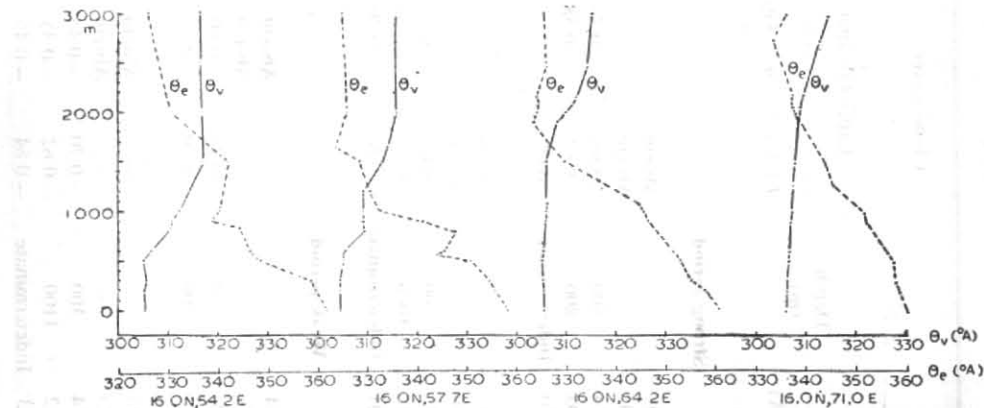


Fig. 7. Profiles of virtual potential temperature (θ_v) and equivalent potential temperature (θ_e) along 16°N —during strong period

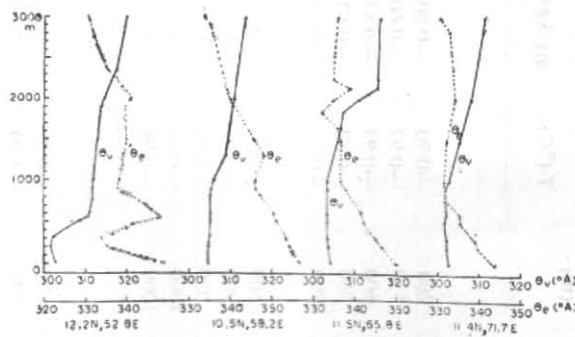


Fig. 8. Profiles of virtual potential temperature (θ_v) and equivalent potential temperature (θ_e) along 11°N —during strong period

the planetary boundary layer is not well defined and the depth of the cloud layer becomes indeterminate.

Average depths of the mixed and cloud layers along with the average height of the base of inver-

sion at each four degree interval along 16°N and 11°N are given in Table 1 for the strong and weak periods. It may be seen that the depths of both the mixed and cloud layers are comparatively smaller at 16°N than those at 11°N . The inversion generally occurs at a lower

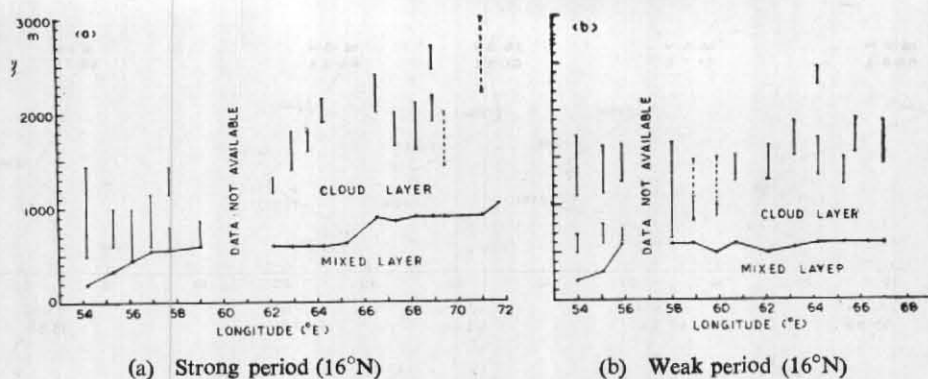


Fig. 9

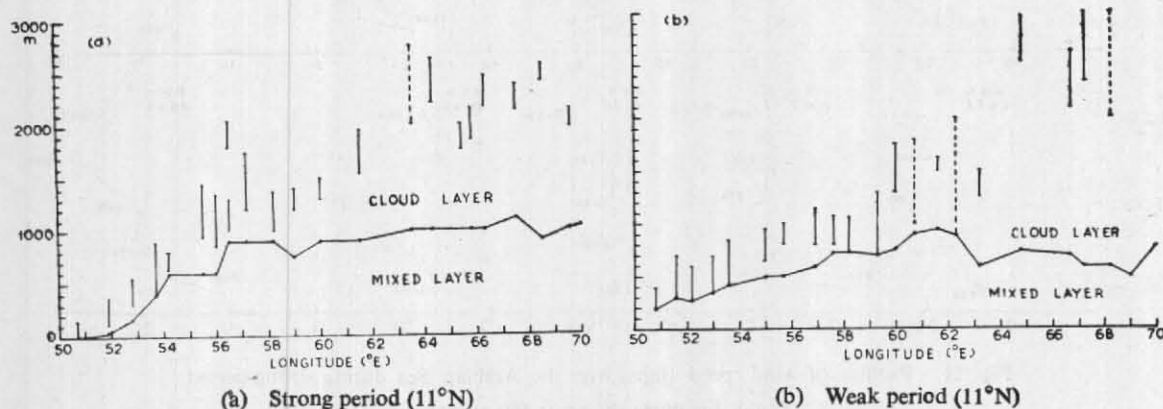


Fig. 10

Figs. 9—10. Spatial distribution of the different sub-layers

(Vertical lines—temperature inversions and dashed-lines—stable layers; lapse rate 0.4°C per 100 m)

height at 16°N as compared to that at 11°N particularly during the strong period.

7. Vertical structure of wind in the planetary boundary layer over the Arabian Sea

Structure of low level wind field over the Arabian Sea was first shown by Bunker (1965) based on the IIOE data. He traced a low level jet (wind speed exceeding 50 kt) off Somalia and thence across the central parts of the Arabian Sea to the coast of India at an average height of about 1000 m above the sea level. More recently, Jambunathan *et al.* (1974) and Desai *et al.* (1976) studied the vertical distribution of winds in the lower troposphere over the Arabian Sea using ISMEX data. The average shape of the vertical profiles of wind speed in the planetary boundary layer in the region north of about 7°N over the Arabian Sea is characterised by a sharp wind maximum at

a height of about 1000 m above the sea surface. The maximum wind speed attained is more than 25 mps in many individual profiles over the central region of the Arabian Sea. A secondary wind maximum, of lesser intensity also occurs at a height of about 100 m above the sea surface in most of the profiles in this region. Large positive vertical shear of wind of the order of 2 mps per 100 m or more occurs in two distinct layers, one below the level of maximum wind and the other in the surface boundary layer. To the south of 7°N latitude and east of 50°E, the profiles indicate a gradual increase of wind speed with height with a relative maximum attained at a height of about 1000 m above the sea surface. Vertical profiles of wind speed at some of the locations in the Arabian Sea are illustrated in Fig. 11. The measured changes in the wind direction in the region north of 7°N indicate a veering of only 5° to 10° in the mixed layer and upto about 15° in the

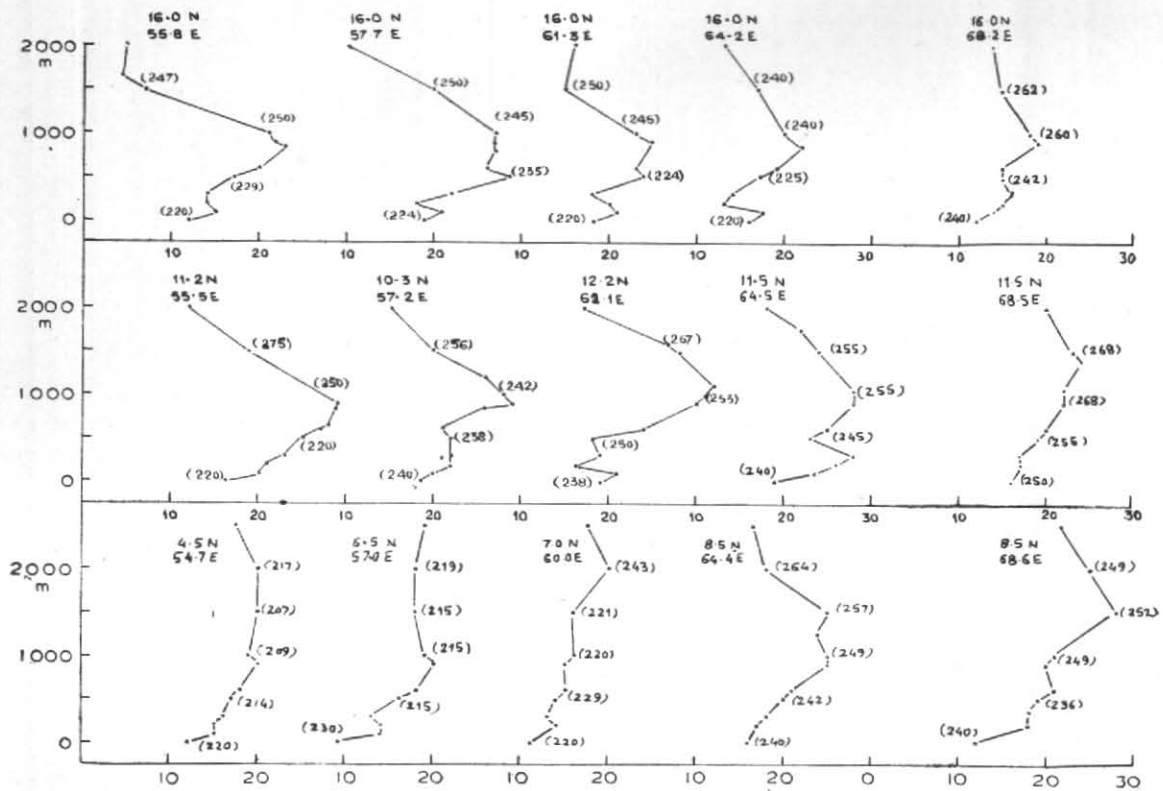


Fig. 11. Profiles of wind speed (mps) over the Arabian Sea during strong period
(Wind directions shown at 500 m interval)

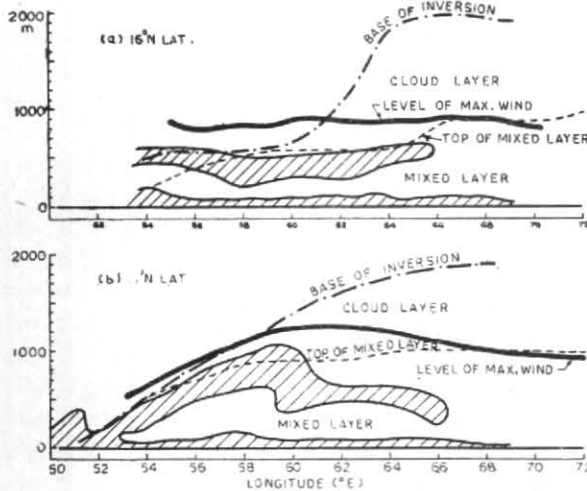


Fig. 12. Schematic diagram showing the base of inversion and height of low level maximum wind (speed ≥ 22 mph) during strong period (hatched portion represents regions of positive vertical wind shear of 2 mps per 100 m or more)

cloud layer. South of 7°N the directions, however, show a backing of about 10° in the mixed layer.

In Fig. 12 a simplified schematic diagram is presented to illustrate the positions of the level of maximum wind at 16°N and 11°N respectively in relation to the different sub-layers of the planetary boundary layer as observed during the period of strong wind flow over the Arabian Sea. In the western region of the Arabian Sea, the maximum wind occurs well within the inversion layer. It occurs within the cloud layer in the central region but nearly coincides with the top of the mixed layer in the eastern region.

8. Summary and concluding remarks

The preceding presentation is the description of the thermodynamical and kinematic structure of the atmospheric planetary boundary layer in the west Indian Ocean during the Indian summer

monsoon of 1973. The study is based on the analysis of more than 200 aerological soundings obtained at closely spaced locations in this region during the period from 4 June to 8 July 1973. During this period well developed southeast trades prevailed over the south Indian Ocean and a steady (in direction) southwesterly flow over the Arabian Sea. The profiles of air temperature, specific humidity and wind speed indicate a remarkably different vertical structure of the planetary boundary layer in the region north of about 10°N over the Arabian Sea from that observed to the south of it. In the region to the north of 10°N, the profiles indicate a strong downward slope of the inversion layer from the coast of India towards the west and demonstrate that the planetary boundary layer in the western region of the Arabian Sea is normally reduced to a shallow mixed layer and a strong temperature inversion. A very different picture is observed in the extreme eastern region of the Arabian Sea, where strong convective mixing weakens the layered structure and the inversion is generally absent. In this region the top of the boundary layer cannot easily be defined based on the temperature and humidity profiles.

In contrast to a nearly constant vertical distributions of specific humidity and wind speed in the mixed layer as observed in other tropical oceans of the world, a strong moisture lapse and a strong upward increase of wind is observed in this layer over this region. Yet, another feature which differs markedly from that observed elsewhere in the tropics, is the small moisture lapse within the inversion layer in this region, which even changes sign and shows an increase with height over the central region of the Arabian Sea during the weak period.

In this study no attempt has been made to discuss the relevant physical processes which lead to the observed variations of the vertical structure of the planetary boundary layer, a topic beyond the goal of this paper.

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DISCUSSION

G.V. RAO : Were the sea surface temperature anomalies examined for their possible relation with the mixing depth?

AUTHOR : No.