

Structure of the southwest monsoon near the equator during Monex 1973

M. C. PANT

Meteorological Office, New Delhi

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ABSTRACT. The structure of the southwest monsoon near the equator over the west Indian Ocean during June 1973 has been studied by utilising MONEX 1973 data. It is found that the equatorial belt extending from the east African coast to about 75°E can broadly be divided into three regions, *viz.*, (i) the western region—extending from the east African coast to about 56°E (ii) the central region—from 56° to about 65°E and (iii) the eastern region—east of 65°E. The vertical fields of wind, temperature and moisture markedly differ from each other over these regions. While over the western and eastern regions deep convective activity is observed, the central region is characterised by a large-scale sinking of air in the mid-tropospheric levels. Due to this dynamic process, the mid-tropospheric westerlies suffer considerable modification and become increasingly warm and dry downstream over the central region.

1. Introduction

The structure of the southwest monsoon near the equator over the Indian Ocean has not hitherto been studied in detail due to lack of adequate data. A few dropsondes during the International Indian Ocean Expedition (IIOE) revealed that the atmosphere near the equator is relatively dry immediately above the marine layer during the Indian summer monsoon. Analysis of satellite cloud data also reveals that there is marked cloud minimum over the equatorial region of the west Indian Ocean during the full swing of the southwest monsoon. In this vast near-equatorial sea area of cloud minimum, one is tempted to infer that the upward motion of air over this region is being inhibited by subsidence—a conclusion supported from theoretical considerations by Koteswaram (1960), Pisharoty (1965), Asnani *et al.* (1965) and Asnani (1968). More recently, Pisharoty (*see ref.*) suggested the existence of a zonal cell, similar in nature to the 'Walker Circulation' (Bjerknes 1969), associated with the monsoon with rising air over the warm equatorial waters and a zone of subsidence over areas of comparatively cold waters. An examination of the mean vertical motion during the monsoon by a ten-layer quasi-geostrophic model, Das (1962) provided evidence of an ascending limb over northeast India and a zone of marked descent over northwest India.

2. Present study

In this paper an attempt has been made to study the thermal and moisture structures of the equatorial troposphere over the west Indian

Ocean during the period 16 June to 2 July 1973, utilising monsoon experiment (MONEX) data. In the Indo-USSR joint expedition over the Indian Ocean during May to July 1973, the research vessel *Okean* cruised along the equator from Long. 46°E to 71°E from 16 to 22 June. It took a return cruise from 71°E to 60°E during 22-25 June and then remained stationary at Long. 60°E till 2 July. It later moved northward for a day along 60°E meridian and then took an eastward cruise from 4 to 8 July along about 8.5°N latitude. 6-hourly radiosonde/rawin observations were taken on board the ship *Okean* during this period.

3. Synoptic situation

In 1973, the southwest monsoon advanced into most parts of the country by 14 June, except the northeast and north India. It was generally weak over the country during 16 to 28 June 1973. An examination of the cloud pictures from NOAA-2 satellite during this period indicated no significant variation in the monsoon activity in the equatorial belt extending from the east African coast to 75°E. Throughout the period a well marked convective area was seen over the eastern sector of the region extending from about 66°E to about 75°E. West of 66°E the area remained generally cloud free except on the first two days of the period of study, *i.e.*, on 16 and 17 June, when a bright cloud mass crossed the equator from south near 52°E and appeared to have moved subsequently in a northeasterly direction.

The cloud pictures indicated revival of the southwest monsoon on the west coast of India

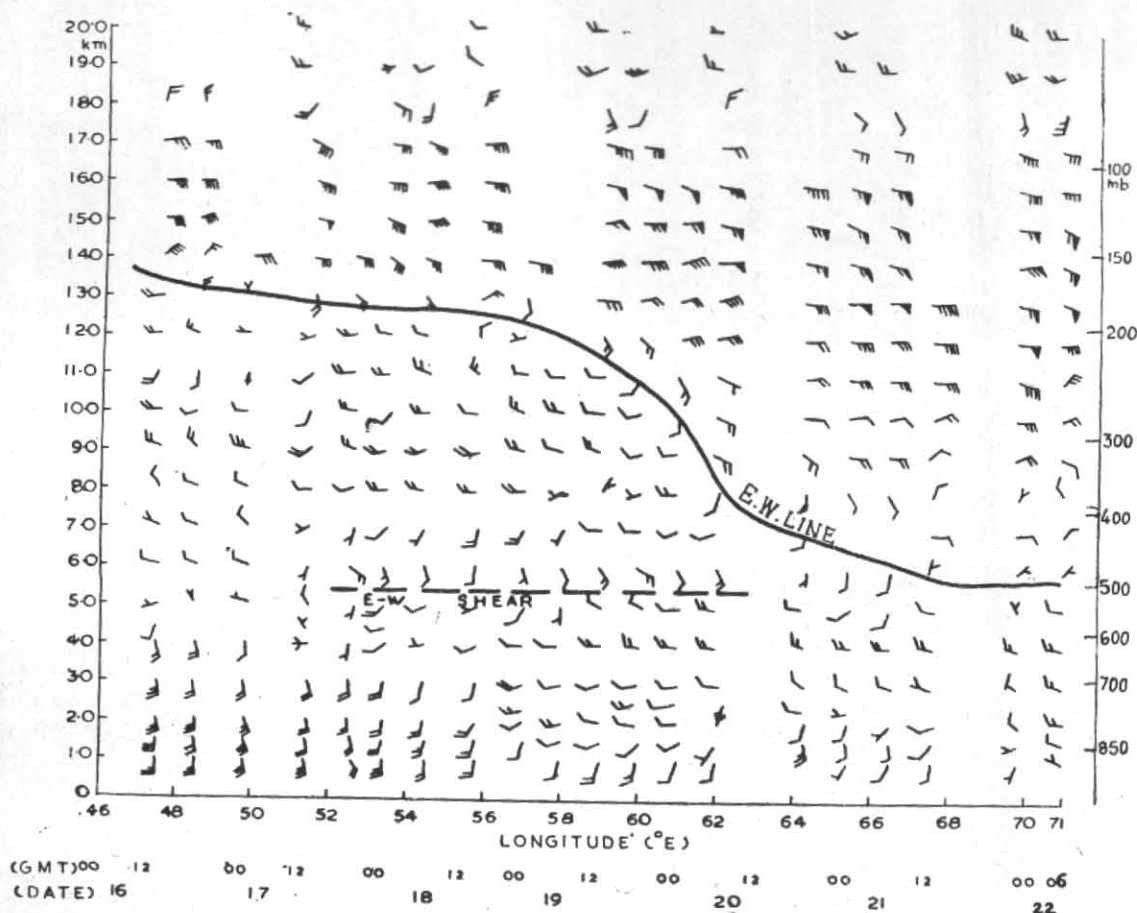


Fig. 1(a). Vertical distribution of wind (kt) at the equator during 16-22 June 1973

after 28 June. During the northward extension of the monsoon activity, the region west of about 65°E over the Arabian Sea and adjoining equatorial belt, however, remained generally cloud free.

4. Analysis of data

Vertical cross-sections of wind, temperature and moisture along the equator have been prepared from the RS/RW observations recorded on board the ship *Okean* during the period of study, and are discussed.

4.1. Vertical distribution of winds

The vertical distribution of winds upto 20 km (Fig. 1 a) along the equator during 16-22 June 1973 reveals the following salient features:

(a) In the lower troposphere south to south-westerlies prevail. These extend from surface to about 700 mb over the western region extending from 46° to about 56°E and show a rapid decrease in their depth eastward of 56°E where they are confined to below 800 mb over the region lying

between 56° and about 65°E. They further decrease in depth east of 65°E.

The southerlies are strongest (25-30 kt) at 2 km and below over the western region (west of 56°E) and over rest of the equatorial section, these are of the order of about 10 kt.

(b) The westerlies prevail above the lower tropospheric southerlies and have their maximum depth over the region west of 56°E, where they extend upto about 200 mb. The westerlies show a rapid decrease in their depth from 56°E to about 65°E. East of 65°E these are seen only upto about 500 mb. The westerlies are of the order of 10-15 kt throughout the section.

(c) In the upper troposphere easterlies extend upto about 100 mb and have their maximum depth over the region east of 65°E and minimum over the region west of 56°E. The easterlies attain their maximum strength of about 70 kt at about 150 mb (15 km) over the region east of 60°E and show a significant decrease downstream over the western region.

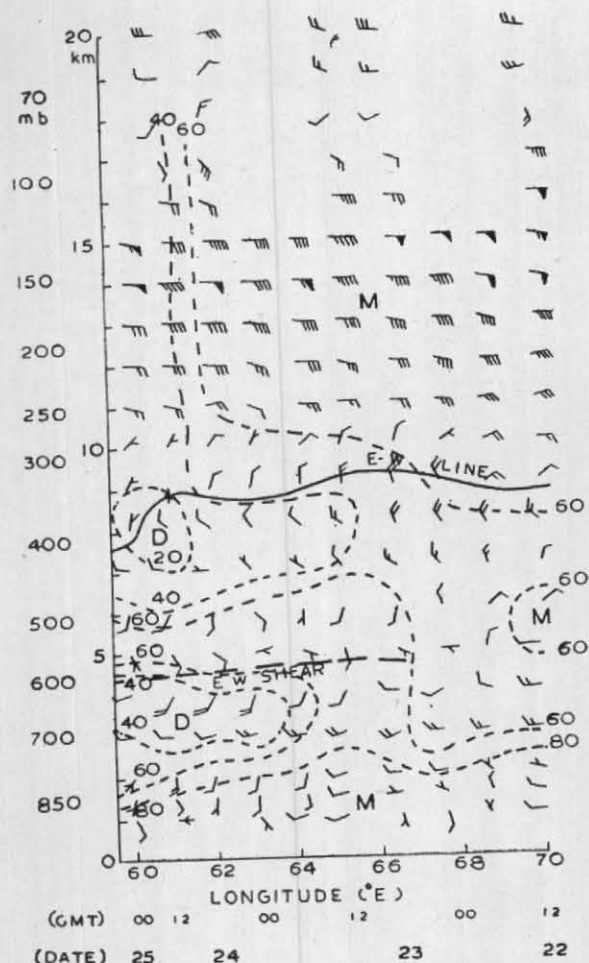


Fig. 1 (b). Vertical distribution of wind (kt) and relative humidity (%) at the equator during 22-25 June 1973

Similar features of wind distribution are observed during the return cruise of the ship from 71°E to 60°E (Fig. 1b).

The existence of the three wind regimes over the equator during the Indian summer monsoon is well known (Koteswaram 1960). The present data, however shows that the wind regimes are not of uniform depths at the equator but markedly vary from one region to the other. It may also be seen that the westerlies at the equator are very much weaker than to the north of it where they attain their maximum strength of 50-55 kt in the lower troposphere over the west and central Arabian Sea (Bunker 1965; Jambunathan and Ramamurthy 1974). The data also confirms the existence of tropical easterly jet (TEJ) at the equator as shown earlier by Koteswaram (1969).

4.2. Fields of temperature and moisture

Temperature — Temperature profiles were constructed from 1000 to 300 mb levels at each

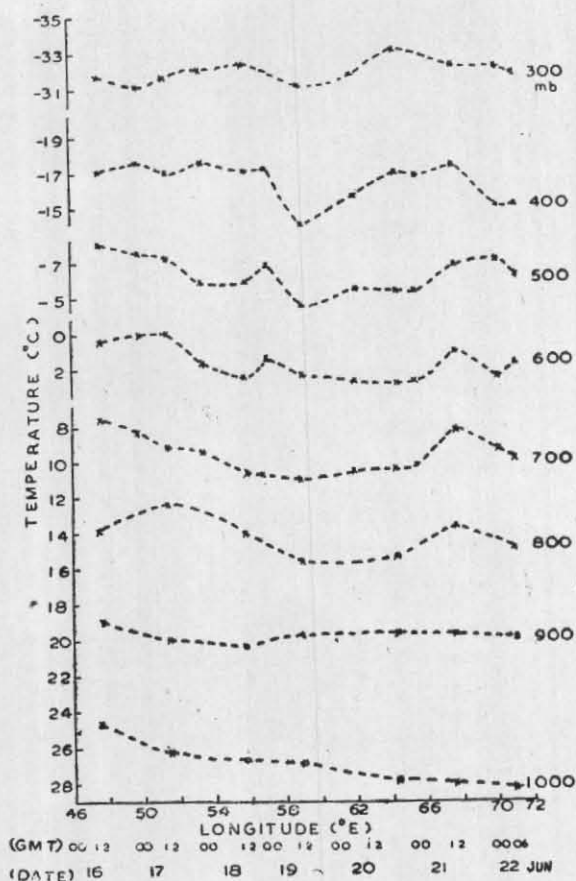


Fig. 2. Temperature profile at 1000 to 300-mb levels during 16-22 June 1973

100 mb interval (Fig. 2) to study the vertical distribution of temperature at the equator. The profiles show the following important features:

- At 1000 mb the temperature gradually increases from west to east. The net rise in temperature from 46° to 71°E is about 4°C.
- Between 800 and 400 mb, there is a gradual increase in temperature from about 56° to about 60°E and gradual fall from 60° to about 68°E.
- No significant variation in temperature is seen at 300 mb level.

Lapse rate of temperature — Average lapse rates (°C/km) are computed for each 100 mb layer from 1000 to 200 mb and are given in Table 1 (lapse rates are computed for each 50 mb layer between 900 mb and 700 mb). It shows the presence of a remarkable stable layer in the lower troposphere over the central equatorial region lying between 56°E and 65°E. It may

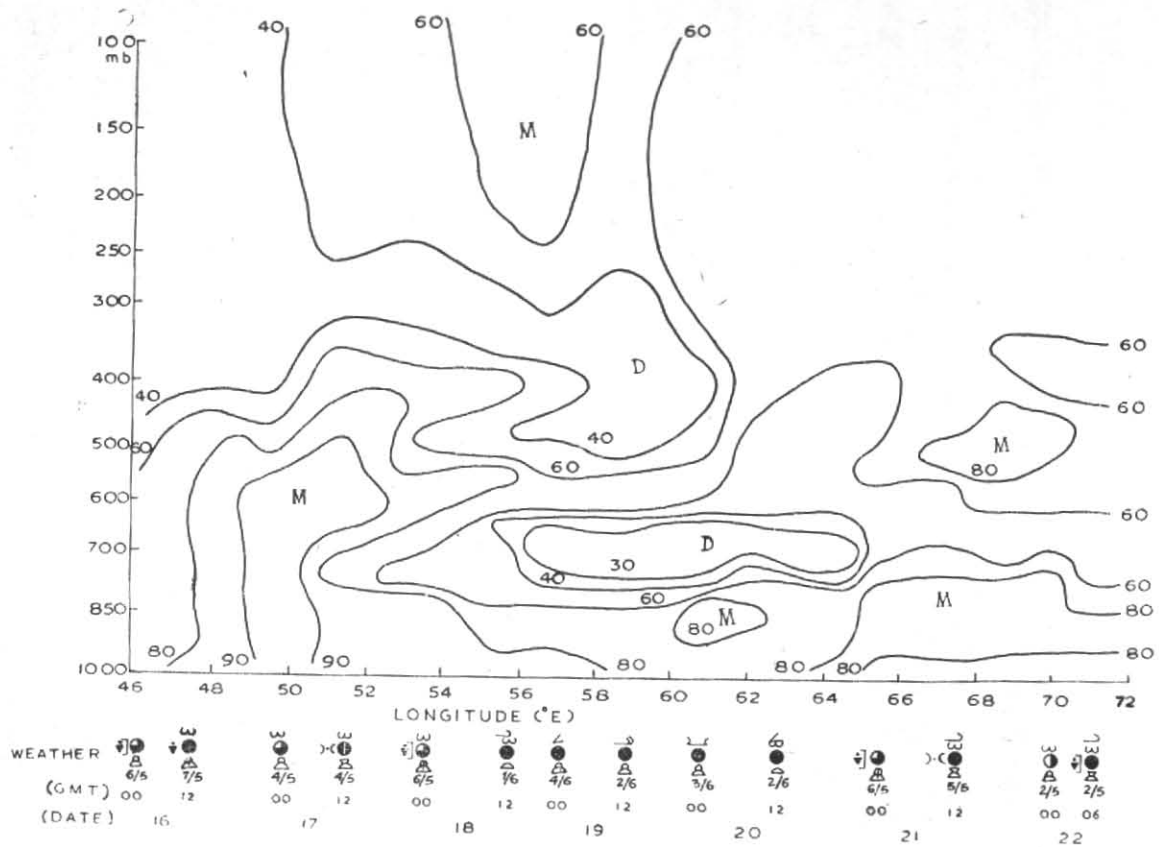


Fig. 3. Vertical distribution of relative humidity (%) during 16-22 June 1973 at the equator

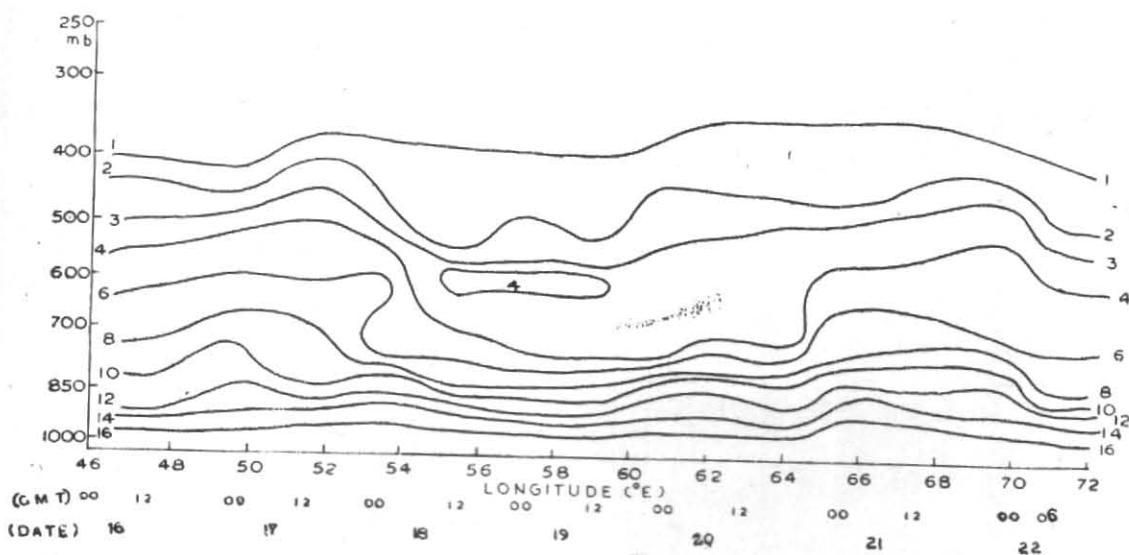


Fig. 4. Vertical distribution of humidity mixing ratio gm/kg at the equator during 16-22 June 1973

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TABLE 1

 Average lapse rate over the equator and Long. ($^{\circ}$ E) during 16-22 June 1973

Layer (mb)	Lapse rate ($^{\circ}$ C/km) and Long. ($^{\circ}$ E)							
	47.5	51.4	55.8	59.0	64.3	65.4	67.6	71.0
1000-900	6.4	7.5	7.1	8.0	8.0	8.2	9.0	9.1
900-850	4.6	7.2	6.0	6.0	5.2	5.8	7.1	5.0
850-800	5.6	6.2	6.6	2.2	3.4	6.3	5.0	4.7
800-750	5.6	2.8	0.5	1.8	0.8	2.1	4.0	4.5
750-700	5.6	3.8	4.4	7.0	1.2	4.3	5.4	4.5
700-600	5.8	7.4	7.6	7.0	6.2	6.1	5.8	6.5
600-500	5.9	5.8	5.9	4.8	5.7	5.6	5.4	5.5
500-400	5.5	5.9	7.8	5.8	7.0	6.9	6.2	5.2
400-300	7.2	7.0	7.5	8.0	8.3	7.6	7.0	8.0
300-200	8.4	8.5	7.6	8.0	8.4	8.8	9.0	8.4

also be noted that there is a gradual increase in the lapse rate (LR) in the surface layer from west to east. The lapse rate is close to dry-adiabatic rate east of 65° E.

Table 2 shows some of the characteristic features of the low-level stable layers (LR $< 2^{\circ}$ C/km) observed during the period 16-22 June 1973. It is of interest to note that there is a gradual deepening of the stable layer from about 54° to 59° E and a gradual weakening thereafter. East of about 68° E no stable layer is found in the subsequent soundings.

Moisture — The vertical distribution of relative humidity at the equator during the period 16-22 June is presented in Fig. 3. West of about 56° E high humidity (> 80 per cent) is observed in a deep layer extending from surface to about 500 mb. The humidity shows a decrease aloft and is less than 50 per cent in the upper troposphere. Over the region lying between 56° E and 65° E and west of about 65° E high humidity is generally confined to below 900 mb. Above this level humidity falls rapidly with height and very low humidity (< 30 per cent) is observed within the layer of 800-600 mb. Humidity shows an increase above 600 mb but falls again above 500 mb level. High humidity is observed east of 65° E in a deeper layer extending from the surface upto about 750 mb. A relatively drier air exists above upto about 600 mb but aloft the air is moist. Similar features of humidity distribution are observed during 22 to 25 June (Fig. 1 b).

TABLE 2

Low-level stable layer and their intensity during 16-22 June 1973

Location (Equator and Long. $^{\circ}$ E)	Stable layers		Intensity ($^{\circ}$ C) temp. of top minus temp. of base
	Base (mb)	Top (mb)	
51.4	800	776	0.0
53.4	800	782	-0.7
55.8	800	763	0.0
57.0	800	743	-1.1
59.0	850	750	-2.0
62.0	821	765	-1.5
64.3	822	803	0.0
	764	748	
65.4	777	733	-0.1

The humidity mixing ratio distribution in the vertical shows some interesting features (Fig. 4). While, over both the western and the eastern equatorial regions, the mixing ratio decreases uniformly with height and quite high value of mixing ratio (about 6 gm/kg) is observed even at about 600 mb level, it decreases rapidly with height over the central equatorial region lying between 56° E and 65° E. Here the entire gradient of mixing ratio is contained in the layer below about 700 mb. Above this level, the mixing ratio of the air is small (about 3 gm/kg) and

TABLE 3

Maximum dew point depression and amount of descent* during June 1973

Date & time (GMT)	Location (Equator & Long. °E)	Max. dew point depression (°C)	Level of occurrence (mb)	Amount of descent (m)	Level of origin (m)
17 1200	51.4	4.0	700	496	3643
18 0000	53.4	11.4	712	1413	4413
18 1200	55.8	12.6	714	1562	4562
19 0000	57.0	16.5	743	2046	4696
19 1200	59.0	18.5	750	2294	4874
20 0000	61.0	17.5	743	2170	4820
20 1800	64.3	18.0	733	2232	4989
21 0000	65.4	9.0	700	1116	4266

*Calculated following Petterssen *et al.* (1947)

remains practically uniform within the layer extending upto 500 mb.

Discussion

Wind, temperature and moisture distributions in the equatorial troposphere during 16 to 25 June suggests that the equatorial belt over the west Indian Ocean can be broadly divided into three regions: (1) The western region—extending from the east African coast to about 56°E; (2) the central region—extending from 56°E to about 65°E and (3) The eastern region—extending eastward of 65°E. The airmass in the lower troposphere over the western region is cool and moist and is of maritime origin, which, after crossing the equator from south enters the Arabian Sea (Findlater 1969). Over the central region the moist southwesterlies are confined to below about 900 mb and above this level a dry westerly airmass prevails in the lower-middle troposphere. This airmass is also of the southern hemispheric origin (deflected SE trades at the southern hemispheric equatorial trough) as has been shown by Ghosh and Pant (1974) based on MONEX data. The temperature profiles at the mid-tropospheric levels, particularly between 800 and 500 mb, also confirm the above view, since no sharp temperature discontinuity is observed at these levels from west to east. Instead, a gradual rise in the temperature of the westerlies occurs downstream east of about 56°E. Consequence of this warming, the westerlies become increasingly dry with time which is reflected in the increase in the dew point depression downwind (Table 3). With an increase in the convective activity over the eastern region there is a rapid upward transport of moisture from the surface layers and the extreme dryness of the westerlies considerably decreases.

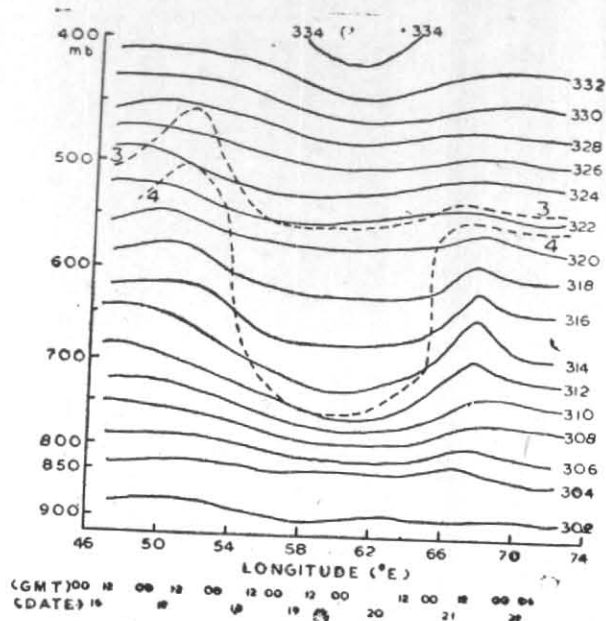


Fig. 5. Vertical distribution of potential temperature (°A) during 16-22 June 1973. Dashed lines are isopleths of 3 and 4 gm/kg (mixing ratio)

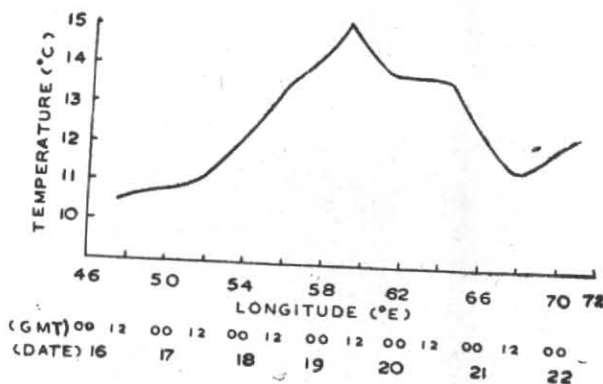


Fig. 6. Temperature profile at 750 mb

5.1. Vertical distribution of potential temperature

Since the westerlies over the central region have a uniform moisture content within the layer 800-500 mb and are dry, the flow may be considered to be adiabatic for a short period of 2-3 days and the air particles should remain on the same isentropic surfaces. It may be seen that the isentropes contained within the layer 800-500 mb have a relatively steep downward slope from about 54°E to 60°E, suggesting a marked descent of the westerlies over this region. From 60°E to about 64°E the isentropes remain nearly horizontal but have a rather steep upward slope east of about 65°E. It may also be noted that while in the upper part of the subsiding layer the stability shows a decrease, it shows an increase near the base as long as the subsidence

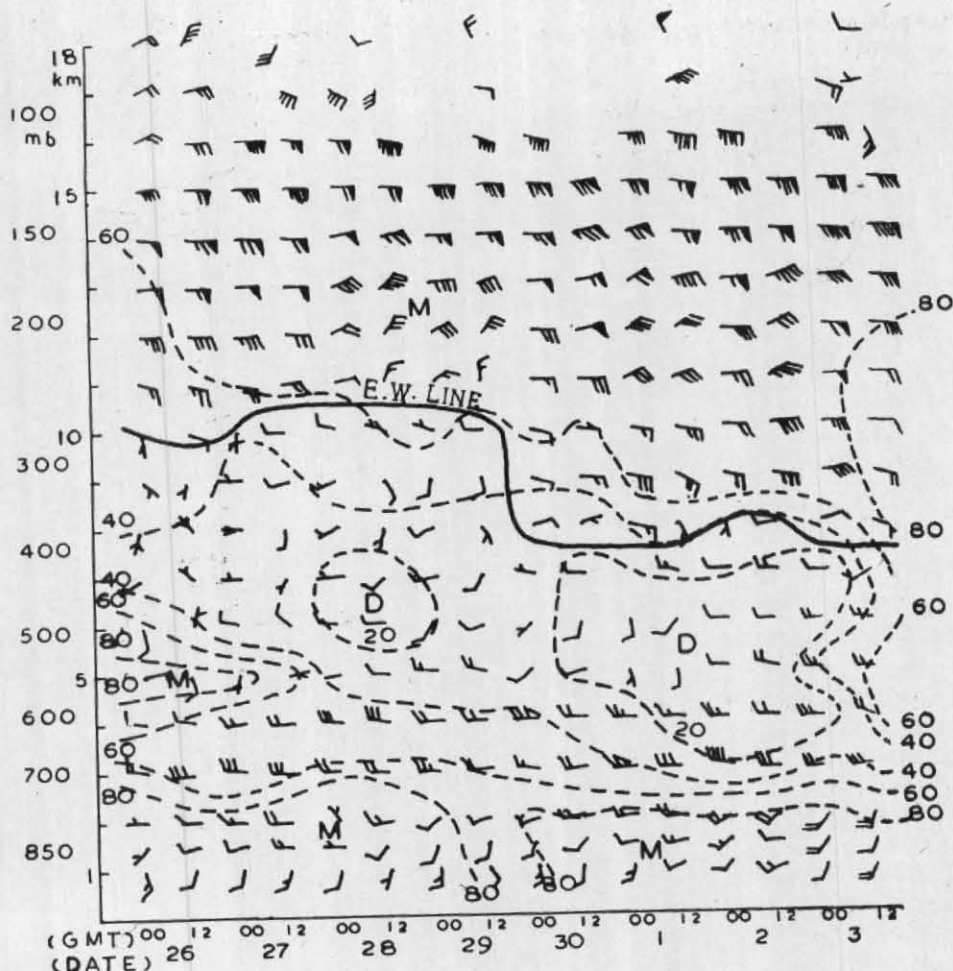


Fig. 7. Vertical distributions of winds (kt) and relative humidity (%) at the equator and 60°E during 26 June to 3 July 1973

continues. The isentropes show a gradual concentration within the layer 850-750 mb. A fractional decrease of the pressure depth contained within the isentropic surfaces of 308° and 312°A also indicates an increase in the horizontal divergence at the base of the subsiding layer. The pressure depth shows a rapid increase over the eastern region.

An approximate amount of descent of the air is computed following Petterssen *et al.* (1947) and is given in Table 3:

$$i. e., \Delta z = 124 (\Delta T) d \quad (1)$$

where, Δz is the amount of descent in m and $(\Delta T) d$ is the dew point depression ($T - Td$) in °C.

The maximum descent of the air amounts to about 2300 m. The highest level of origin of the subsiding air is near 5.0 km. Since the amounts of descent computed using the above relationship may be somewhat less than the actual amounts because of possible evaporation of

cloud or precipitation near the base, the actual levels of origin may be slightly higher than those given here.

The temperature changes associated with the subsiding airmass are better reflected at a level which is close to the level of occurrence of the maximum dew point depression. Temperature picked up for such a level (taken as 750 mb in the present case) from the ascent curves are presented in Fig. 6. A steep rise of temperature by about 4°C from about 54° to 60°E is spectacular.

5.2. Vertical time section at equator and 60.0°E

Vertical distributions of wind and relative humidity at the equator and 60°E for the period 26 June to 2 July 1973 are presented in Fig. 7. It is seen that except for the first two days, the air remains extremely dry above about 700 mb and below 400 mb even during the revival of the monsoon activity over the west coast. However, there is a significant increase both in the

lower tropospheric westerlies and upper tropospheric easterlies during this period.

6. Conclusions

The study brings out the following conclusions :

(1) The whole equatorial section of the west Indian Ocean can be broadly divided into three distinct regions, where the southwest monsoon shows markedly different fields of wind, temperature and moisture in the vertical.

(2) The three wind regimes of the monsoon circulation of the equatorial troposphere are (i) the highly moist southerlies in the lower troposphere, (ii) the overlying dry westerlies in the middle troposphere and (iii) the relatively moist easterlies in the upper troposphere.

(3) Maximum cross-equatorial flow occurs in the lower troposphere at the western equatorial region (east coast of Africa to about 56°E). This flow progressively weakens eastward and is minimum at the eastern region (eastward of 60°E).

(4) Tropical easterly jet exists in the upper troposphere over the region east of 60°E and considerably weakens to the west.

(5) The temperature at the 1000 mb surface and the lapse rate of temperature in the surface layers, both show a progressive increase from west to east. The lapse rate is close to dry-adiabatic rate over the eastern region.

(6) While deep convective activity is observed over both the western and the eastern equatorial regions, the central region is characterised by subsidence in the middle troposphere. Under the influence of this dynamic process the mid-tropospheric westerlies of the central region become increasingly warm and dry downstream. A typical subsidence discontinuity appears in the lower troposphere over this region.

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