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Discussion of upper air data of 2 and 4 July 1963 from the point of presence of airmasses and structure of the cyclonic vortex off the Bombay coast

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ABSTRACT. Upper air data over the Arabian Sea for 2 and 4 July 1963 when there was a cyclonic vortex off the Konkan coast, have been discussed with reference to the synoptic charts. It is seen that the data show definite evidence of airmasses and 'reversal level' over the sea as has been observed in the past over the subcontinent. Miller and Keshavamurthy's (1967)kinematic analysis charts for 500-mb level for 2 and 4 July and their conclusions from the same would appear untenable. Their not recognising the 'reversal level' has led them to consider that the vortex and thermal structure are similar to the 'subtropical cyclone'.

1. Introduction

It has been known since long that during the months May to September, the continental air over the Indian subcontiment is warmer than the moist air at the surface, but higher up it becomes colder than the latter due to a difference in the lapse rates in the two airmasses ; the level at which the change takes place, is called the 'reversal level' and its height varies from one occasion to the other (Ramanathan and Banerji 1931 ; Mal *et al.* 1932 ; Desai and Mal 1933 ; Ramanathan and Ramakrishanan 1933 ; Sawyer 1947 ; Desai 1951, 1967 a). It is also known that the topographical features of the subcontinent contribute significantly in making the monsoon circulation self-sustaining in the lower levles of the atmosphere (Simpson 1921 ; Banerji 1930, 1931 ; Petterssen 1953 ; Desai 1967 b, c, d). During the International Indian Ocean Expedition (IIOE), dropsondes and flight level data were collected on 2 and 4 July 1963 over the Arabian Sea when there was a cyclonic vortex off the Bombay coast, and it is proposed to examine the same with reference to the synoptic charts with a view to see if they show existence of airmasses over the sea as has been observed over land and from the point of structure of the cyclonic vortex off Bombay on those days.

2. Discussion of data with reference to synoptic charts

(1) *2 July 1963*—From the rainfall recorded on the west coast it is seen that an active phase of the Arabian Sea Monsoon (ASM) began after 03 GMT of 30 June and widespread and locally heavy rain occurred on the entire west coast upto 20°N by 03 GMT of 1 July. With this a trough appeared at the surface off the west coast at 12 GMT of the 1st. From the upper winds existence of a trough could also be seen off Konkan at 600 and 500 mb, there being continental air over the Arabian Sea to the north of about 17°N and west of 70°E ; at 700 mb there was a trough axis running along about 20°N from 70°E to 75°E and then southeastwards across Andhra to about 17°N, 82°E ; and at 850 mb the trough axis ran northeastwards from near 20°N , 65°E over northeast Arabian Sea to near 27°N , 73°E over west Rajasthan. There was no feeding of air from the Bay side in the trough off Konkan at 600 and 500 mb, the southerly winds on the north Konkan coast being the westerly winds over the east Arabian Sea which has curved cyclonically. Actually there was no steady flow of air from the Bay over the north of the Peninsula on 29 and 30 June.

Between the 1st and 2nd mornings widespread rain again fell over the west coast upto 20°N; rainfall had considerably increased between 12 and 17°N due to further strengthening of the ASM under the influence of a low pressure over the northwest Bay off Orissa and generally decreased northwards upto 20°N due to cyclonic curving of winds. At 03 GMT a trough lay off Konkan at the surface. Flight level data for the 2nd near 500 m, 550 mb and 500 mb are available and they are given in Tables 1, 2 and 3 respectively. Dropsondes data at two locations in the central Arabian Sea for 0925 and 1131 GMT and radiosonde data for 12 GMT for Bombay are given in Fig. 1.

It is seen from 12 GMT surface chart for the 2nd that there was a trough about 200 km west of

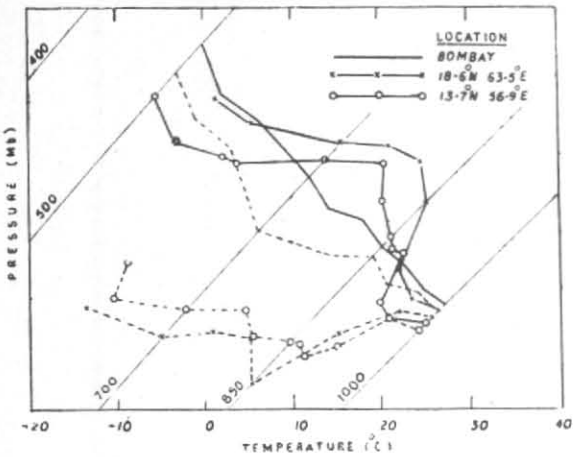

Fig. 1. Tephigram for 2 July 1963

TT—Continuous line
T_dT_d—Broken line

TABLE 1

Flight data near 500-m level

Time (GMT)	Lat. (°N)	Long. (°E)	DDD (°)	FFF (kt)	Temp. (°C)	Pressure (mb)
1000	16·4	60·1	240	027	22	952·95
1030	17·5	61·9	246	022	23	953·25
1100	18·2	63·7	253	023	23	952·30
1145	18·7	66·8	273	018	23	953·50
1200	18·7	67·8	272	028	23	954·25
1230	18·4	69·9	357	015	20	943·70
1245	18·3	70·9	305	013	21	953·45
1300	18·4	71·8	199	000	21	954·70

the Konkan coast between about 16 and 21°N. This trough would appear to have moist air (deflected trades) on both the sides of its axis.

It will be seen from Fig. 1 that over the central Arabian Sea, there was moist airmass in about the first 50 mb with unstable lapse and moisture concentrated in that layer and dry air above upto 600 mb with nearly adiabatic lapse and an inversion between the two airmasses. From the synoptic charts and aircraft wind observations (Table 1) it is seen that the lower moist air was the deflected trades airmass and the upper drier air was continental air from Arabia and West Pakistan side. The inversion would not appear to be due to subsidence in the dry continental air; if it was so, the specific humidity should have remained the same in the subsiding continental air above the deflected trades layer. Actually the specific humidity has decreased regularly with height in the continental air in both the soundings except at 13·7°N, 56·7°E where it has increaseed from 850 to 760 mb. Thus the inversion was an airmass one. Bombay had moist air in all the levels with nearly saturation adiabatic lapse; the depth of the moist layer at Bombay was more than over the central Arabian Sea, moisture being transported upward from the lower layer of deflected trades due to the combined influence of the trough in the lower levels and vortex above and of the Western Ghats. The deflected trades airmass was colder than the moist air at Bombay upto about 950 mb. As a result of difference in the lapse rates in the dry arirmass above the deflected trades in the central Arabian Sea and moist airmass at Bombay, the former became colder than the latter at about 620 mb at 18·6° N, 63·5°E and 670 mb at 13·7°N, 56·9°E (Fig. 1.).

It would appear that the airmass stratification over the central Arabian Sea was not affected by synoptic features off the Konkan coast.

From Table 1 it will appear that near 500-m level also, there was a trough with axis running parallel to the coast passing approximately through 18°N , 72°E ; Veraval and Bombay winds at 0·6 km would show that the trough extended to 21°N, 72°E. The trough at 500 m would appear to be in the same moist airmass, *i.e.*, the deflected trades as at the surface.

From the winds at Veraval it would appear that above about 1·0 km, continental air was getting into the trough area to the north and northwest across Kathiawar, Kutch and Sind ; to the south was the westerly moist air and to the east the same moist air which had curved cyclonically. No air from the Bay side was getting into the trough area.

It would appear from 850-mb chart that the trough in the lower levels had changed into a closed circulation with centre near 19·5°N, 71·5°E. There was absence of easterly moist air from the Bay side in the central area.

The chart for 700 mb showed better cyclonic circulation than at lower levels and the

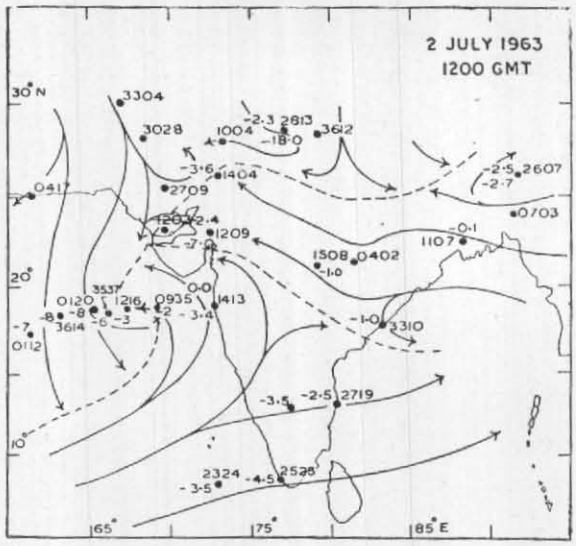

Fig. 2. 500-mb chart for 2 July 1963

For land stations 6·0 km winds have been plotted. To the right of station, wind direction in tens of degrees and speed in knots—(DDFF); to the left TT/T_dT_d in °C. Partitions between different airmasses have been drawn as usual considering direction, temperature, weather and cloud information and previous trajectory

TABLE 2

Flight data near 550-mb level

Time (GMT)	Location near (°N)	(°E)	DDD (°)	FFF (kt)
1126	22·4	66·2	069	017
1214	21·4	66·3	006	032
1239	20·8	67·2	002	033
1259	20·5	68·5	027	032
1314	19·8	69·2	029	024
1329	19·5	69·7	006	016

centre was near 18·5°N, 72°E; 700-mb aircraft data in the lower portion of Table 3 would appear to support the position of the centre. It would appear from Karachi, Bhuj and Veraval winds that northeasterly winds over the northeast Arabian Sea off west Kathiawar-Kutch-Sind coast were somewhat stronger than the northeasterly winds near the central region as judged from aircraft wind near 700 mb given in Table 3. There was no moist air from the Bay side in the circulation.

The circulation centre was near 18°N , 71·5°E at 600 mb. From the winds at Bhuj and Karachi at 600 mb and aircraft winds near 500 mb given in Table 2, it would appear that northerly to northeasterly winds in the northwest at a distance beyond about 300 km were much stronger than the winds within that distance of the centre (aircraft wind near 600 mb given in the lower position of Table 3) ; conditions were thus similar to those at 700 mb. The easterly to southeasterly winds in the central area were not more than 20 kt. There was no easterly moist air from the Bay side in the vortex field.

In the 500-mb (6·0 km) chart in Fig. 2 are also plotted aircraft data near that level given in Table 3. It will be seen that the moist air at this level was warmer than the dry continental air and this was due to a difference in the lapse rates of the two airmasses nearly dry adiabatic in the latter and near saturation adiabatic in the former. The vortex was an elongated one with centre near 18°N, 69·5°E. The continental air to the west would not appear to have advanced towards the west coast although the moist air advanced rapidly westwards above the reversal level, its limit at 550 mb (Table 2) being to the east of 19·5°N, 69·7°E ; at 600 mb, the limit of the moist air towards west near 19°N, 71·5°E. Thus at 600 and 550 mb, the cyclonically curved cooler westerly moist air had not advanced appreciably westwards ; no moist easterly air from the Bay side was getting into the cyclonic field.

TABLE 3

Flight data near 500-mb level

Time (GMT)	Lat. (°N)	Long. (°E)	DDD (°)	FFF (kt)	Temp. (°C)	Pressure (mb)
1000	14·96	58·37	022	009	—07	497·40
1030	16·10	59·99	001	008	—07	497·15
1100	17·25	61·56	015	012	—07	497·15
1130	18·32	63·20	359	014	—08	496·75
1200	18·51	65·30	014	020	—08	496·55
1215	18·62	66·34	351	037	—06	496·85
1230	18·74	67·33	117	016	—03	496·70
1245	18·75	68·30	021	009	—02	497·45
1300	18·89	69·21	089	035	—02	497·25
1315	18·79	70·00	083	017	—02	497·35
		Data at levels below 500 mb while aircraft was descending				
1324	18·74	70·66	071	006	03	599·25
1330	18·65	71·04	014	008	08	702·60
1345	18·71	72·05	225	016	14	825·40

Relatively high temperatrue atD elhi would probably appear to be due to presence of subsided air over the area; low dew point would support this influence.

Between 2 and 3 July mornings rainfall was widespread on the coast, being 8 to 13 cm between 11° and 17·5°N and only light to the north due to cyclonic curving of winds over the area; rainfall had also extended over Kutch, Kathiawar and Gujarat upto Ahmedabad. There was no rain in Gujarat north of Broach, Kathiawar (except for a light shower at Veraval) and Kutch between the 1st and 2nd mornings.

In order to understand changes in airmass stratification of the type near 18·6°N, 63·5°E (Fig. 1) under the influence of the vortex off Konkan while it moves eastwards, temperatures there and over the area 18·4°—18·9°N, 70·0—72·4°E at different levels taken from Tables 1, 2 and 3 are given in Table 4.

It will be seen from Table 4 that the difference in temperature between the central Arabian Sea and off the Konkan coast increased to 10°C at 825 mb and then decreased higher up, the reversal taking place beween 600 and 500 mb. Off the coast the forced ascent of air due to cyclonic shear and the influence of the Western Ghats (massing of air in the lower levels) and mixing, and cooling the continental air due to evaporation of falling rain and its humidification at the same time, increased the depth of the moist layer to more than 500 mb, its depth to start with being equal to the depth of the deflected trades airmass.

The above analysis for the 2nd, may now be compared with that of Miller and Keshavamurthy's (1967):

They have given dropsonde data at 18·6°N, 63·5°E in Fig. 38A of their paper. It is stated that above the inversion dry air was subsiding, and that at 850 mb air from Arabia and Mekran coast was overrunning the shallow moist layer of the southwesterlies. While the airmasses at the location as indicated by them and in this paper are about the same, there is no evidence in the TT and D.P. data given in Fig. 1 that air was subsiding above the layer of moist air to give inversion. The inversion was an airmass one as mentioned earlier.

Miller and Keshavamurthy have shown two cyclone centres at 500 mb in Fig. 15 of their paper; one near 67°E and the other near 69°E, the latter being the main one. From Table 3 and Fig. 2 it will appear that the first vortex near 67°E is near the boundary between the dry

TABLE 4

Level (mb)	Location (A)	Temp. (°C)	Location (B) between 18·4°–18·8°N and 70·0°–72·4°E (Lat.)	(Long.)	Temp. (°C)	Differencee in temp.of locations (A) and (B) (°C)
500	18·6°N, 63·5°E	—5	18·8°N	70·0°E	—2	—3
600	,,	6	18·7°N	70·7°E	3	3
700	,,	16	18·7°N	71·0°E	8	8
825	,,	24	18·7°N	72·0°E	14	10
955	,,	24	18·4°N	71·8°E	21	3
985	,,	26	18·5°N	72·4°E	24	2

and moist airmasses ; it is possible that this vortex was of short duration and of small extent as it happens at the boundary between the continental and moist airmasses (Desai 1968). There was one east-west elongated vortex with centre near 18°N, 69·5°E. Further, in their Fig. 15, they have also plotted data of aircraft flying near 550-mb level (Table 2) to the north of the aircraft flying near 500-mb level. This would not appear correct as the reversal level was just above 550-mb level and the conditions at 500-mb were markedly different.

Their streamlines at 500-mb in Fig. 15 show flow of air from southeast across northwest of the Peninsula. This is not justified because as seen from Fig. 2 and earlier discussions for conditions at different levels; the moist air in the vortex field was that from the east Arabian Sea curved cyclonically. It appears that streamlines method of analysis has given exaggerated pictures and conclusions from the same are not tenable.

From the data of aircraft flying at different levels it can be seen that the boundary between dry and moist airmasses between about 18° and 19°N was between about 66°E and 72°E. The cloud and weather observations for 2 July given by Miller and Keshavamurthy (1967) were presumably associated with boundaries at different levels between airmasses and convergence areas near them.

(2) *3 July 1963*—Between 2nd and 3rd mornings, widespread rain fell on the west coast as mentioned earlier. On the 3rd morning a feeble low circulation was noticeable even at the surface with centre near 20°N, 71°E, a ship reported near 19°N, 70°E rain and NW/50 kt wind. Bombay upper winds had veered at all the levels since the 2nd evening and at 00 GMT were S to SW upto 500 mb and S'ly above upto 9·0 km. This showed that the cyclonic circulation was deep and had moved northwards. The low circulation over the northwest Bay was also better defined when compared with the 2nd morning.

At 12 GMT, the centre of the low at the surface was near 21°N, 71·5°E; Bombay winds upto 3·0 km (data not available for higher levels) were 250°, speed increasing from 27 kt at 0·3 km to 55 kt at 2·1 km and decreasing to 39 kt at 3·0 km.

No aircraft data are available over the northeast Arabian Sea for the 3rd.

(3) *4 July 1963*—By 03 GMT a depression had formed over the north Bay with centre near 21·5°N, 89°E. The low at the surface at the mouth of the Gulf of Cambay was persisting near 21·5°N, 71·5°E. Rainfall on the west coast was widespread and locally heavy upto 18°N between the 3rd and 4th mornings. Rainfall decreased in Gujarat, but continued in Kathiawar and Kutch. Rain recorded at Bombay on 4th morning was the same (1—2 cm) as that recorded on the 3rd morning. Bombay rain should have increased in view of winds upto 3·0 km at 12 GMT of the 3rd mentioned earlier. It, however, appears that after 12 GMT, the winds had considerably weakened and at 00 GMT of the 4th were 240°–250°/ 8–21 kt upto 3·0 km, being 190°—200°/8 to 13 kt above upto 6·0 km. This fact was probably responsible for no increase in rainfall at Bombay.

TABLE 5

Time (GMT)	DDD (°)	FFF (kt)
0930	029	017
0944	312	018
1028	349	023
1043	354	009
1058	335	024
1114	259	019
1129	330	004
1144	122	006
1159	195	014

The low at the surface had weakened by 12 GMT of the 4th but was persisting near Bhavnagar. The centre was displaced southwestwards with height; the circulation was also apparently weakening in higher levels. Bombay upper winds at 12 GMT were 220°–260°/17 to 33 kt upto 3·0 km and 160°–200°/15 to 17 kt above upto 6·0 km. An aircraft flew near 19°N from 62°E towards Bombay near 550-mb level; its data are given in Table 5. The dropsondes data collected by the aircraft near 19°N, 64°E; 19°N, 66°E and 19°N, 69°E at 10, 11 and 12 GMTrespectively are plotted in Fig. 3. The 500-mb level (6·0 km) chart is given in Fig. 4.

It would appear from Table 5 that at the flight level near 550 mb, the aircraft passed the boundary between the dry and moist airmasses at about 1135 GMT near 68°E. From Fig. 3 it is seen that the airmass stratification at 19°N, 64°E and 19°N, 66°E was of the same type as at 18·6°N, 63·5°E, on the 2nd (Fig. 1). On comparing dropsondes data of 2 and 4 July with those of 26 June in the west Arabian Sea off the Arabian coast, it would appear that there was the same type of airmass stratification on all the days, deflected trades in the lower levels and dry continental air above with an inversion between the two airmasses; the inversion in all the cases was an airmass one, the warmer continental air overrunning the deflected trades in the surface layer. The cyclonic vortex off the Konkan coast did not affect airmass stratification at 18·6°N, 63·5°E on the 2nd or at 19°N, 64°E and 19°N, 66°E on the 4th, the low centre on the latter day being near Bhavnagar at the surface and near 19°N, 69°E at 550-mb level.

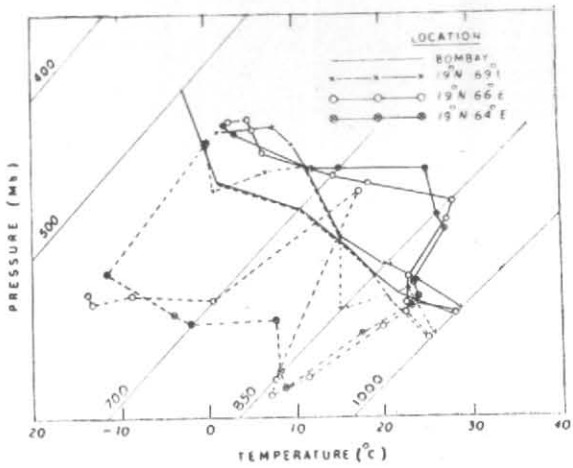

Fig. 3. Tephigram for 4 July 1963

TT—Continuous lines
T_dT_d —Broken lines

At 19°N, 69°E marked changes occurred when compared with conditions at 19°N, 66°E. There was considerable increase in humidity, disappearance of inversion and considerable lowering of temperature between about 900 and 675 mb. Between 625 and 675 mb humidity was not very high (at 600 mb, TT=7·8°C and T_dT^d=0·8°C) and lapse rate was near dry adiabatic between 600 and 560 mb.

From the 6·0-km level chart in Fig. 4, it will appear that there was no vortex near Bombay; there may, however, be a depression over land with centre near 22°N, 73°E.

Bombay had deep moist layer extending upto at least 500 mb (Fig.3) and had marked westerly component in winds in the lower levels. As the vortex was weakening and its centre displaced southwestwards with height upto about 550 mb as mentioned above it is possible that the Ghats contributed significantly in producing 500-mb deep layer at Bombay (compare data for 19°N, 69°E with those of Bombay given in Fig. 3).

Miller and Keshavamurthy (1967) have given 500-mb level chart for 12 GMT of the 4th in Fig. 16 of their paper. They have shown two centres, one near 19°N, 64°E and the other near 19°N, 69°E, based on data of aircraft flying near 550-mb level which are plotted on their 500-mb level chart. This is not justified as there were considerable differences between conditions at 500 and 500-mb levels, there being no vortex off Bombay at the latter level; even at 550 mb the low near 19°N, 69°E was very weak as can be judged from winds betwwen 1114 and 1159 GMT (Table 5).

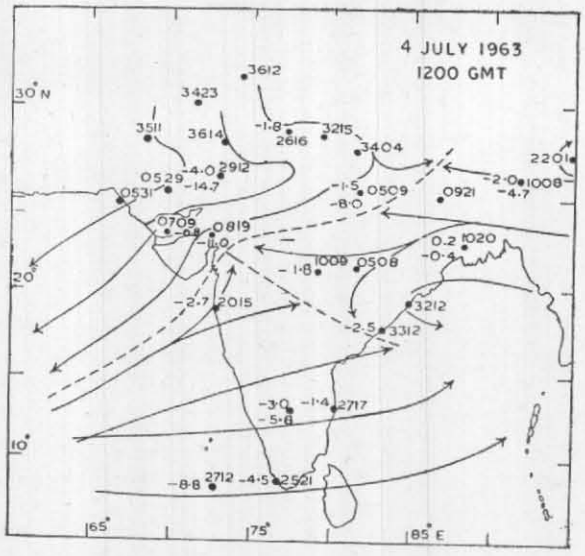

Fig. 4. 500 mb chart for 4 July 1963

For land stations 6·0km, winds have been plotted. To the right of station wind direction in tens of degrees and speed in konts—(DDFF); to the left TT/T_dT_d in degree C. Partitions between different airmasses have been drawn as usual considering direction, temperature, weather and cloud information and previous trajectory

The low shown near 19°N, 64°E on the basis of winds at 550-mb level would appear to be in the dry continental air as seen from dropsondes data (Fig. 3), there being no moist air west of about 69°E. The flow patterns shown by Miller and Keshavamurthy in their Fig. 16 off Bombay are not tenable as they are based on aircraft data near 550-mb level.

(4) *5 July 1963*—Between the 4th and 5th mornings widespread rain occurred from Trivandrum to Mangalore and from Ratnagiri to Surat and over south Kathiawar; rainfall was very heavy from Harnai to Dahanu and at Veraval and Keshod; Harnai having 7 cm, Alibag 10, Colaba 11, Santacruz 9, Dahanu 31, Veraval 9 and Keshod 10 cm. Heavy to very heavy rain was probably associated with rapid filling up of the vortex and change in the circulation pattern over the area. The Bay depression was near Saugar Island.

On the 5th there was no vortex; Bombay winds at 12 GMT were 250° to 270° upto 5·4 km and 340° at 6·0 km.

3. Concluding Remarks

It will be seen from the foregoing discussion of the dropsondes and aircraft flight-level data for the 2nd and 4th with reference to the synoptic charts that the same can be satisfactorily explained on the basis of existence of airmasses over the northeast Arabian Sea. The airmass stratification of the central Arabian Sea type near 18·6°N, 63·5°E on the 2nd, was also present in the east Arabian Sea upto about 19°N, 68°E on the 4th. Although the vortex was weakening rapidly on the 4th and the moist layer did not extend to 550 mb at 19°N, 69°E and the air was not saturated in all the levels below 770 mb and above 650 mb, Bombay had moist layer with nearly 100 per cent humidity extending from about 900 to 500 mb, the influence of the Western Ghats being probably responsible for the increased depth.

If Miller and Keshavamurthy (1967) and Ramage (1966) were aware of the earlier work referred to in the introduction about the pecularities of the airmasses and the 'reversal level' during the months May to September and of the role of the topographical features of the subcontinent, it is felt that they would not have been led to believe that the thermal structure of the vortex in the northeast Arabian Sea was similar to that of the 'subtropical cyclone' or that the depressions in the north Bay are warm-cored and in the northeast Arabian Sea cold-cored. The structure of the Arabian Sea monsoon system proposed by Ramage (1966) and Miller and Keshavamurthy (1967) cannot be accepted in the light of the IIOE data and the facts of weather (particularly rainfall) and climatological and topographical features of the subcontinent (Desai 1967 b, d).

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