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Thermodynamic structure of the atmosphere over India during southwest monsoon season

V. SRINIVASAN and V. SADASIVAN

Meteorological Office, Poona

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ABSTRACT. The differences in the thermodynamic structure of the atmosphere over India and the adjoining areas between active and weak monsoon (southwest) periods in the various meteorological sub-divisions are presented.

The mean dry bulb and dew point temperatures and equivalent potential temperatures during active and weak monsoon were calculated at all the radiosonde stations in India and neighbourhood and studied. The results show that whatever be the monsoon activity, there is no significant change in the dry bulb temperature at any level and the moisture content in the lower tropospheric levels remains high without any appreciable variation. The main change is in the moisture content in the mid-tropospheric levels. The implication of these results in the vertical circulation associated with active and weak monsoon and in the radiation budget are brought out, since the vigorous ascending air in the areas of strong monsoon ultimately subsides slowly over the regions of weak monsoon. The region of the seasonal monsoon trough has been identified as the area of maximum total energy both in active and weak monsoon periods as well as the area where the variation in the total energy between active and weak monsoon is least. This is also the area where convective instability is present upto greater heights than elsewhere. The estimated heights of *Cb* tops are highest in the region of the seasonal monsoon trough. It is also shown that there is no reversal of virtual temperature gradient over the northwest India in the mid-tropospheric levels during the SW monsoon season.

1. Introduction

Since the last few years, there has been a steady increase in the network of radiosonde stations (RS) in India. With the introduction of the new A-type instruments, the quality of observations has improved and dew point temperatures are also available to much greater heights than before. The new audio-frequency modulated radiosonde instrument uses thermistors for recording temperature and hygristors for recording humidity. With hygristors, dew point temperatures can be recorded over a greater range (upto -60°C) and hence dew point temperatures are now available utpo great heights. The use of these sensors have also led to greater accuracy in the observational values. In the case of audio-modulated (amplitude modulated) instruments, the estimated accuracy of the instrument is given as ± 1°C for temperature and and $\pm$ 5 per cent for relative humidity at temperature + 40 to 0°C and $\pm$ 10 per cent at temperature 0°C to -20°C (US Air Force 1971). The recent few years' data, therefore, provide a good basis for a study of the thermodynamic structure of the atmosphere over the country afresh. The present work was undertaken to study the conditions during the southwest monsoon season, with special reference to the differences in the vertical distribution of temperature and humidity between active and weak monsoon conditions in the various parts of the country. The preliminary results of the authors (Srinivasan and Sadasivan 1973) are presented now in detail. For this study, the data from all the radiosonde stations* in India (except Srinagar, Bangalore, Ernakulam and Madras**) and a few ex-India stations were utilised; the data belong to the recent few years after the audio-frequency modulated instruments were introduced at the Indian stations and they generally cover 2 to 4 monsoon seasons. While the study was in progress, ships' observations of MONEX 1973 also became available and these have been utilised. While the data for the land and island stations belong to the mid-monsoon months of July and August, after the southwest monsoon is completely established, the data for MONEX belong to the advancing phase of the monsoon

*These stations cover all types of geographical distribution — Minicoy and Port Blair may be considered to be oceanic stations, Bombay etc, coastal stations and New Delhi, Nagpur etc interior land stations.

**These stations have been omitted either because of data limitations or because of insignificant monsoon activity in the months of July and August. It has been found that some of the features discussed in this paper apply to Madras also during N.E. monsoon season (Srinivasan and Ramamurty 1973).

TABLE 1

Details of data used

Station	Region of monsoon activity	Period of data (Months-July & August)	No. of cases of monsoon: Active	Weak	Data source
Indian stations					
Ahmedabad	Gujarat Region	1969-71	32	100	IMD Records
Bhubaneshwar	Orissa	1972-73	17	51	,,
Bombay (Santacruz)	Konkan	1968-71	29	105	,,
Calcutta (Dum Dum)	Gangetic West Bengal	1968-70	33	70	,,
Gauhati	Assam & Meghalaya	1968-71	33	54	,,
Goa	Goa & South Konkan	1971 & 74	22	44	,,
Hyderabad (Begumpet)	Telangana	1971-72	7	25	,,
Jodhpur	W. Rajasthan	1969-71	63*	128	,,
Lucknow	East Uttar Pradesh	1969-71	39	76	,,
Minicoy	Lakshadweep	1971-72	19	55	,,
Nagpur	Vidarbha	1969-71	21	89	,,
New Delhi	Punjab & Haryana	1968-70	36	97	,,
Port Blair	Bay Islands	1971-72	21	43	,,
Trivandrum	Kerala	1971-72	24	67	,,
Visakhapatnam	North Coastal Andhra Pradesh	1971-72	11	69	,,
Ex-India stations					
Bangkok	S. W. Thailand	1961-63	33	53	Monthly Radiosonde Data. Thailand Met. Department
Colombo	West Sri Lanka	1961-65	16	40	I.I.O.E. Manuscript Data
Gan	Gan Island	1968-71	15	40	U. K. Overseas Supplement
Saigon	Saigon area	Jul 66	4	4	Sci. Report No. 3, Hawaii Institute of Geophysics
MONEX Ships' data					
Mean Position					
Lat. 10°N, Long. 60°E	S.W. Arabian Sea	Jun-Jul 1973	4	37	Mss. Sheets
Lat. 10°N, Long. 67.5°E	S. E. Arabian Sea	Do.	13	13	,,
Lat. 17°N, Long. 60°E	N. W. Arabian Sea	Do.	0	20	,,
Lat. 17°N, Long. 67·5°E	N. E. Arabian Sea	Do.	7	15	,,

*Cases of normal monsoon considered, as active monsoon conditions are practically *nil* in west Rajasthan and are also for a single year. To this extent, the two sets of data are not strictly homogeneous. The details of data used are given in Table 1.

2. Analysis

The data of each RS station is representative of the atmospheric conditions over the particular area of the meteorological sub-division in which the station is situated. For instance, Bombay is considered to be representative of the conditions over Konkan, Calcutta of Gangetic West Bengal etc as indicated in Col. 3 of Table 1. Days of active to vigorous* monsoon conditions as well as weak monsoon conditions in the various meteorological sub-divisions (or sea areas in the case of MONEX ships' data) were grouped separately and the mean vertical distributions of dry bulb and dew point temperatures were computed at each radiosonde station for occasions of strong monsoon and weak monsoon over the particular area (or meteorological sub-division) represented by the station. Thus, we get two means for each radiosonde station — one for active monsoon and the other for weak monsoon. From this data, the mean distribution of equivalent potential temperature (θ_e) in the vertical was also calculated utilising the tables prepared by Rao (1953). These mean values for active and weak monsoon conditions are discussed in this paper.

In order to test the scatter of values used in arriving at the mean temperatures for active and weak monsoon, the standard deviations (S.D.) were worked out for Bombay as a sample case, and are given in Table 2. The S.D. values are fairly reasonable and hence the data used in the study may be considered to be of acceptable degree of accuracy.

3. Discussion

3.1. *Dry bulb temperature*

The differences in the mean dry bulb temperatures (active-weak) at the standard levels between strong and weak monsoon at the various radiosonde stations are given in Table 3. The table clearly shows that the differences in dry bulb between strong and weak monsoon is small and in most cases do not exceed 1°C at any level.

The means of the differences (active *minus* weak) at the standard levels for all the stations are also included in the table in the last column; they show a certain amount of internal consistency with negative values in the lower levels which gradually decrease and change over to positive values at higher levels, implying that during active monsoon in the lower levels (surface to 700 mb) the air is slightly cooler and above this (500 to 200 mb) it is slightly warmer. This feature is seen in the values for many of the individual stations also, in a general way.

3.2. *Moisture content*

The mean relative humidity values at the standard levels over the radiosonde stations during strong and weak monsoon are given in Table 4**. The differences in the relative humidity between strong and weak monsoon are also included in this table. If we consider that differences in relative humidity less than 10 per cent are not significant, we note that at most of the stations, there is no significant difference in relative humidity in the lower troposphere (upto 850 mb) between a strong and weak monsoon day. Also at all the stations, relative humidity is of the order of 75 to 80 per cent or more in the lower troposphere even on weak monsoon days.

The heights upto which relative humidity is 75 per cent or more at the various radiosonde stations during active and weak monsoon conditions are illustrated in Figs. 1(a) and (b). These figures bring out the following features :

(*i*) Under active monsoon conditions, high values of relative humidity (75 per cent or more) are found upto greater heights over northeast India, east Madhya Pradesh and adjoining areas than elsewhere; the atmosphere is very moist upto 300 mb over these areas. This depth decreases as we go south or west from this area. MONEX data suggest another area of low values (less than 400 mb) in the East Central Arabian Sea. It is interesting to note that the areas with heights less than 500 mb are also generally the regions of higher mean rainfall.

(*ii*) During weak monsoon conditions, although the heights to which the high moisture content (*i.e.*, relative humidity > 75 per cent) extends are much lower, their spatial distribution pattern over the country is similar to the one during active monsoon conditions. Even during the weak

*(*i*) For the sake of facility of language 'active to vigorous' monsoon conditions will be referred to as 'active' monsoon in the rest of the paper. Strong monsoon is an alternate term for active monsoon.

(*ii*) The India Meteorological Departmental convention based on rainfall for classifying the monsoon activity is followed in this paper. The main criteria are :

Weak monsoon—Rainfall less than half the normal. Active/strong monsoon—Rainfall $1\frac{1}{2}$ to 4 times the normal. Vigorous monsoon Rainfall >4 times the normal. In the case of MONEX Data, activity was classified on the basis of ships' reports and satellite clouding.

**In this connection refer to Rao's (1952) results in respect of Bombay and Poona.

TABLE 2

Standard deviation (of temperatures) for active and weak monsoon over Bombay

(Period of data 1968-71)

Temp. (°C)	Pressure levels (mb)											
	SFC/ 1000	900	850	800	700	600	500	400	300	200	150	100
Active monsoon												
Dry Bulb	1·0	1·8	1·5	1·3	1·4	1·3	1·3	1·6	2·0	2·7	3·5	4·0
Dew Point	1·0	1·5	1·4	1·6	2·7	3·5	3·3	4·0	4·1	—	—	—
Weak monsoon												
Dry Bulb	1·0	1·2	1·2	1·6	1·8	1·8	1·7	1·5	2·7	2·6	3·0	3·1
Dew Point	0·7	1·4	1·6	2·1	4·5	5·8	4·3	5·4	4·0	1.7	—	—

TABLE 3

Difference in mean dry bulb temperatures (°A) between active and weak monsoon at different pressure levels

Stations	Pressure levels (mb)													
	SFC/ 1000	950	900	850	800	750	700	600	500	400	300	200	150	100
Indian stations														
Delhi	−1·4	−2·2	−2·5	−1·3	−0·9	0·3	−0·1	0	0·3	0	0·1	1·5	−2·6	−0·5
Jodhpur	−0.8	0	0·1	−0·1	−0·5	−1·1	−0·1	0·1	−0·3	0·4	0·1	1·2	0·2	0
Ahmedabad	−1·2	−0·2	−0·7	0·4	0·2	−0·8	−1·2	0·1	0·1	0·3	0·6	−0·1	−0·3	0·7
Lucknow	−1·0	−1·5	−1·2	−1·0	−1·0	0·7	−0·7	−1·1	−0·4	0·1	0·6	0	1·0	−1·1
Bhubaneshwar	−1·2	−1·0	−1·9	−0·9	−0·5	0·2	0·2	0·3	0·3	1·1	1·2	1·3	1·1	−0·7
Nagpur	−0·8	−0·8	−0·7	−0·4	−0·2	0	0·6	0·7	0·1	−0·9	0	0	−0·7	−1·1
Bombay	-0·9	0	0·2	0·6	1·0	0·6	0	0·4	0·6	0·5	1·4	1·1	0·6	0·4
Visakhapatnam	0	—	−0·5	−0·3	−0·1	—	1·0	1·0	1·1	0·6	1·1	0·5	1·3	−0·8
Calcutta	0·9	−0·6	−0·3	0	0	0·2	0	0·2	0·9	1·2	1·3	0·3	0·1	−0·5
Gauhati	-0·9	−0·4	−0·1	−0·6	−0·6	−0·7	−0·7	−0·4	0·2	0·5	0·3	−0·6	−0·9	0·1
Begumpet	−1·1	—	−0·5	−0·2	−0·5	—	0·2	0	−1·2	1·0	1·2	0·5	0·8	−0·4
Trivandrum	−0·3	0	−0·1	−0·4	−0·3	−1·4	−1·0	−0·8	0·1	0	0·3	0	−0·9	1·0
Minicoy	−1·2	−0·5	0·3	0·5	0·6	0·5	0·6	0·5	0·3	1·0	0·2	0·7	0·1	2·3
Port Blair	−0·8	−0·4	−0·3	−0·6	−0·6	−0·8	1·0	−0·9	0·3	0·5	0·5	−0·2	−1·0	−0·2
Goa	−1·3	−0·5	0·2	0·0	−0·1	−0·1	−1·4	−0·6	−0·7	−0·5	−1·4	0·2	−0·2	−2·4
Mean	−0·9	−0·6	−0·5	−0·3	−0·2	−0·2	−0·3	0	0·1	0·4	0·5	0·4	−0·1	−0·3
Ex-Indian stations														
Gan	−2·0	—	−0·2	−0·1	−0·8	—	−0·8	−1·2	−0·7	0·1	1·2	0·8	−1·0	−2·3
Colombo	−1·1	—	0·9	−1·0	−0·3	—	−0·9	−0·6	0	0·4	0·9	−0·8	−0·3	0·3
Bangkok	−0·8	—	−0·2	0·3	−0·2	—	−0·3	−0·1	0·2	0·2	0·5	0.3	0	0·1
Mean	−1·3	—	0·2	−0·3	−0·4	—	−0·7	−0·6	−0·2	0·2	0·9	0·1	−0·4	−0·6
MONEX Ships' data														
Mean Position														
Lat. 10°N, Long. 60°E	0·7	—	0·1	−0·8	−0·8	—	0·2	2·0	0	1·2	1·2	0·7	−2·1	−3·5
Lat. 10°N, Long. 67·5°E	−0·6	—	0·3	−0·3	−0·1	—	0	−0·5	−1·0	−0·8	0	0·3	1·5	−4·2
Lat. 17°N, Long. 65°E	−1·2	—	−0·7	−0·4	−2·7	—	−2·2	0·4	0·3	−0·2	−0·8	−1·0	−1·6	−1·7
Mean	−0·4	—	−0·1	−0·5	−1·2	—	−0·7	0·6	−0·2	0·1	0·1	0·0	−0·7	−3·1

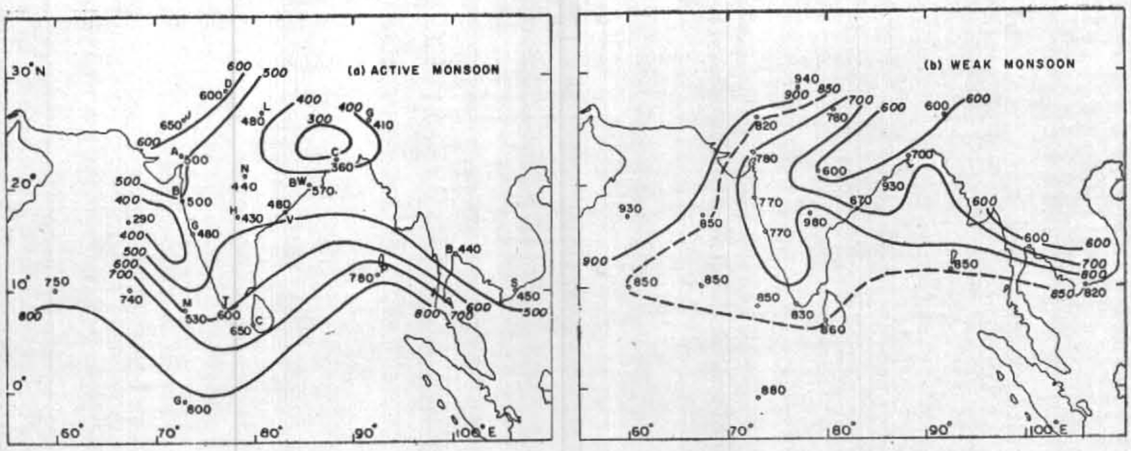

Fig. 1. Heights (mb) upto which relative humidity is 75 per cent or more

monsoon conditions, high humidity values (75 per cent or more) extend to about 600 mb (which is the maximum) over a large part of northeast India, east Madhya Pradesh and the adjoining areas. It is interesting to note that almost identical results were obtained in a totally different connection, in a study of monsoon depressions. Relative humidity was 75 per cent or more from surface upto 600 mb to the north of the monsoon depressions (where monsoon is weak) and upto 400 mb to the south of the monsoon depressions where monsoon is strong (Srinivasan *et al.* 1971). The isopleths in this chart also show that the heights of the moist layer gradually increase from West Arabian Sea to the west coast of India. A comparison between Figs. 1(a) and 1(b) suggests that the air mass modifications over the Arabian Sea (*viz.*, air picking up moisture from the underlying sea surface and the thickness of the moist layer increasing as one goes east from West Arabian Sea towards the Indian coast) is more a characteristic feature of weak monsoon conditions rather than strong monsoon.

(*iii*) It is only above the levels indicated in Fig. 1(b), that air becomes dry during the weak monsoon. In other words, the lower troposphere over India and neighbourhood, the depth varying from 850 to 600 mb, remains quite moist whatever be the monsoon activity. Since there is no significant change either in relative humidity or in dry bulb temperatures we may conclude that there is no replacement of one airmass by another over the country (except perhaps in northwest India) in the lower troposphere when the monsoon activity changes. Examining the data for individual stations, we note that the transition from the lower moist layer to the higher dry layer during weak monsoon is pronounced in some cases (*e.g.*, Bombay, Ahmedabad) and is less marked in the other cases (Gauhati, Calcutta, Nagpur).

From the above analysis of the moisture content, we may state the following results :

(*a*) During the southwest monsoon season, there is a large amount of moisture in the lower troposphere over the whole country. The moist layer is deepest over northeast India, east Madhya Pradesh and adjoining areas in both active and weak monsoon. Even during weak monsoon, the top of the lower moist layer is well above 850 mb level over the country outside the extreme northwestern parts (represented by Delhi).

(*b*) On active monsoon days, the lower tropospheric moisture is pumped upwards by synoptic disturbances. The moisture reaches the highest levels over northeast India, east Madhya Pradesh and the adjoining areas which is the region of maximum cyclonic vorticity in the lower levels caused by the location of the seasonal monsoon trough and passage of depressions and lows across the area. Along and off the west coast, in East Central Arabian Sea, the low level trough and the mid-tropospheric cyclonic circulation cause the pumping of the moisture to high levels.

3.3. *Vertical motion*

Williams (1970) in his studies of cloud clusters and clear areas in the trade wind region of the western north Pacific, has obtained a similar result regarding temperature and humidity distributions. He has also shown that, in cloud clusters, the upward velocity increases with height, from surface upwards, reaches a maximum near 400-300 mb and above this level decreases, reaching zero value near 200-100 mb levels. In clear areas there is downward velocity from surface upto 300 mb and

TABLE 4

Mean Relative Humidity (%) in active (A) and weak (W) monsoon with the difference (D)

Stations/ location		Pressure level (mb) SFC/ 1000	950	900	850	800	750	700	600	500	400	300
						Indian stations						
New Delhi	A	92	92	85	85	85	82	80	73	70	62	57
	W	83	73	67	70	72	70	55	57	52	47	43
	D	9	19	18	15	13	12	25	16	18	15	14
Lucknow	A	92	89	87	87	87	77	77	75	77	56	42
	W	88	82	79	77	76	74	71	58	50	47	33
	D	4	7	8	10	11	3	6	17	27	9	9
Jodhpur	A	82	83	84	84	82	82	78	70	66	69	44
	W	67	73	77	77	63	56	58	48	47	43	35
	D	15	10	7	7	19	26	20	22	19	26	9
Calcutta	A	97	92	90	87	87	87	85	82	87	82	63
	W	92	87	85	83	81	77	68	70	70	61	56
	D	5	5	5	4	6	10	17	12	17	21	7
Ahmedabad	A	95	88	89	89	87	84	83	76	76	68	48
	W	85	87	77	82	80	58	50	52	53	48	44
	D	10	1	12	7	7	26	33	24	23	20	4
Gauhati	A	95	87	87	89	88	90	86	86	86	73	58
	W	92	87	87	83	80	82	77	75	68	50	40
	D	3	0	0	6	8	8	9	11	18	23	18
Bombay	A	93	90	90	86	87	78	77	77	75	65	44
	W	86	86	86	86	85	65	52	55	53	50	47
	D	7	4	4	0	2	13	25	22	22	15	—3
Nagpur	A	98	93	83	87	87	87	87	82	82	67	47
	W	92	87	83	83	83	82	78	75	63	48	50
	D	6	6	0	4	4	5	9	7	19	19	—3
Bhubaneshwar	A	93	90	87	86	87	87	87	77	69	58	60
	W	87	76	70	70	70	72	67	66	54	50	43
	D	6	14	17	16	17	15	20	11	15	8	17
Begumpet	A	92	—	87	86	82		75	80	85	72	56
	W	76	—	70	65	65		60	53	45	40	40
	D	16	—	17	21	17		15	27	40	32	16
Trivandrum	A	96	88	87	85	83	80	72	75	68	53	56
	W	93	88	83	78	68	56	46	52	36	34	—
	D	3	0	4	7	15	24	26	23	32	19	—
Minicoy	A	92	85	83	80	82	80	80	77	78	68	60
	W	82	78	79	74	66	56	47	46	32	37	48
	D	10	7	4	6	16	24	33	31	46	31	12
Port Blair	A	95	86	82	82	78	72	67	73	77	65	55
	W	87	86	80	75	68	58	48	47	47	55	48
	D	8	0	2	7	10	14	19	26	30	10	7
Vizag	A	84	—	83	83	83	—	86	83	78	63	44
	W	84	—	76	76	76	—	76	70	57	50	45
	D	0	—	7	7	7	—	10	13	21	13	—1
Goa	A	96	88	88	87	88	87	81	74	77	63	61
	W	86	86	87	84	80	71	55	47	47	44	49
	D	10	2	1	3	8	16	26	27	30	19	12

TABLE 4 (*contd*)

		Pressure Level (mb)										
		SFC/ 1000	950	900	850	800	750	700	600	500	400	300
Ex-India stations												
Gan	A	83		85	73	75	—	70	70	68	68	57
	W	77		79	68	60	—	51	44	33	39	46
	D	6		6	5	15	—	19	26	35	29	11
Colombo	A	83		81	83	81		80	70	68	63	62
	W	75		80	70	63		56	53	52	52	53
	D	8		1	13	18		24	17	16	11	9
Bangkok	A	92		81	82	82		82	82	78	71	58
	W	87		79	79	75		74	74	71	60	51
	D	5		2	3	7		8	8	7	11	7
Saigon	A	94		93	88	82		83	81	83	66	47
	W	94		88	83	67		64	52	44	42	62
	D	0		5	5	15		19	29	39	24	15

MONEX Ships' observations

Mean Position		*1000*	*950*	*850*	*800*	*700*	*600*	*500*	*400*	*300*	*250*	*200*	*150*	*100*mb
Lat. 10°N,	A	79	87	86	87	65	67	75	54	73	68	68	71	65
Long. 60°E	W	81	80	75	70	62	53	42	48	59	57	58	59	57
	D	−2	7	11	17	3	14	33	6	14	11	10	12	8
Lat. 10°N,	A	81	87	86	85	66	73	69	76	80	76	67	71	69
Long. 67·5°E	W	76	83	75	65	49	43	40	63	69	64	64	64	64
	D	5	4	11	20	17	30	29	13	11	12	3	7	5
Lat. 17°N,	A	—	—	—	—	—	—	—	—	—	—	—	—	—
Long. 60°E	W	83	71	50	35	32	56	58	38	35	34	39	42	43
	D	—	—	—	—	—	—	—	—	—	—	—	—	—
Lat. 17°N,	A	87	92	94	94	81	81	91	92	76	66	65	64	64
Long. 67.5°E	W	82	88	77	52	36	45	58	60	60	62	59	56	55
	D	5	4	17	42	45	36	33	32	16	4	6	8	9

upward motion above. In contrast to the upward motion in cloud clusters, the downward motion in clear areas is much smaller in magnitude and is more or less uniform at most levels.

Though we have not computed vertical velocities in our studies, on the analogy of Williams' study, we can postulate a general slow subsidence on weak monsoon days. In fact, on a few occasions of prolonged dry spells, the tephigrams of Jodhpur, Ahmedabad and Bombay show a stable layer or even an inversion in the lower troposphere. Thus, the absence of low level convergence, general dryness of the mid-troposphere which erodes cloud tops, as well as slow general subsidence, all these combine effectively to suppress the growth of clouds on weak monsoon days inspite of plentiful low level moisture and the increased instability, as will be shown in para 3.4 (*iii*). It is well known that on any day, while monsoon is active in some parts of the country, it is weak in some other parts. The slow subsidence in the region of weak monsoon and the vigorous ascending current in the area of active monsoon form two limbs of a vertical circulation.

Gray (1970) has postulated that the latent heat of condensation in the ascending rain-producing air is stored up as an increase in potential energy and does not warm up the immediate environment. It is the compensating descending current that warms the atmosphere, but this warming is also nullified by radiational cooling. The result is that in the tropics there is little difference in the vertical temperature distribution between ascending rain producing and compensatory descending dry currents. The observational results we have produced in this paper are in agreement with Gray's postulate and show that in this respect, the Indian southwest monsoon field is not different from the tropical regions elsewhere over the globe.

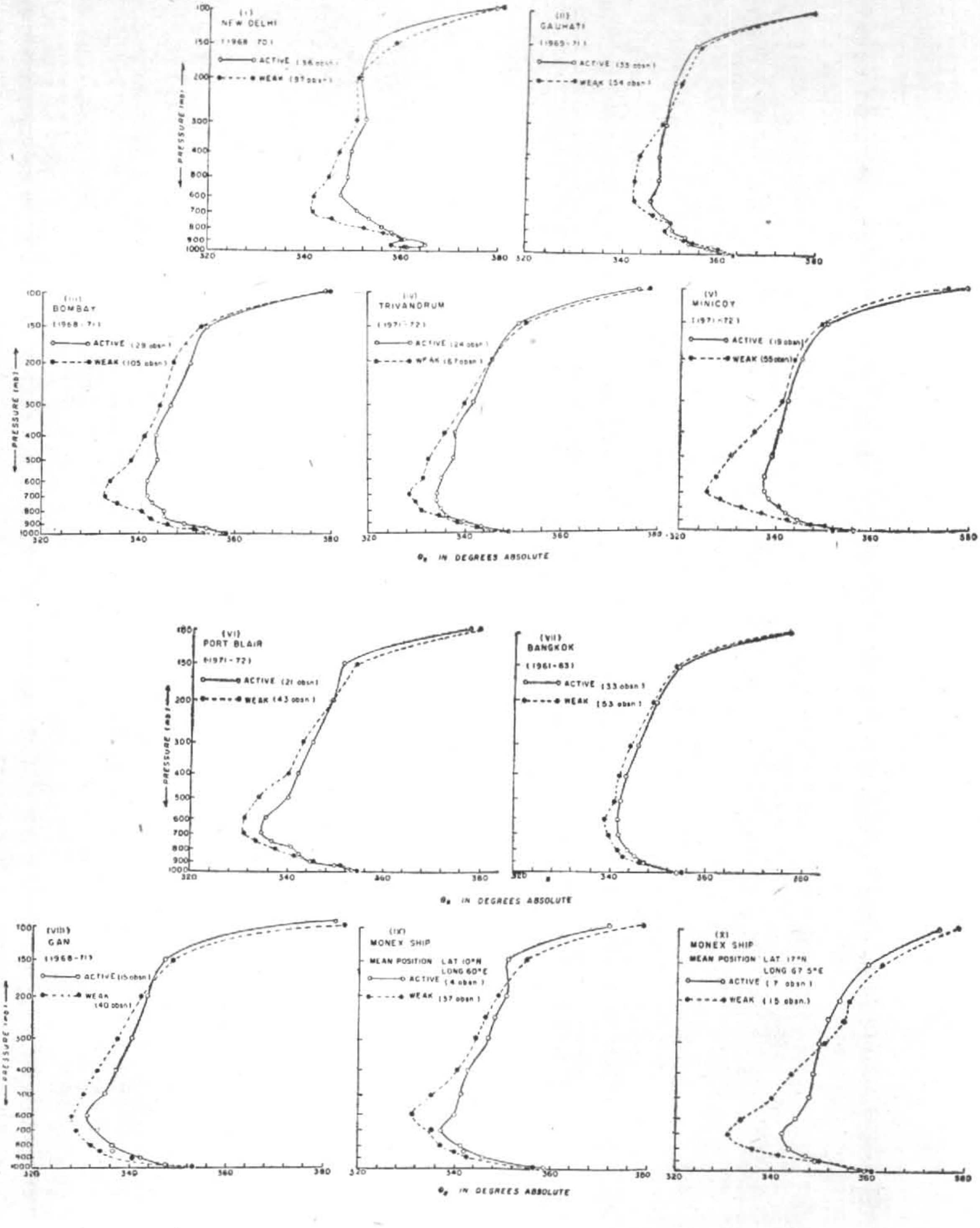

Fig. 2. The equivalent potential temperature (θ_e) distribution for active and weak monsoon days at selected stations

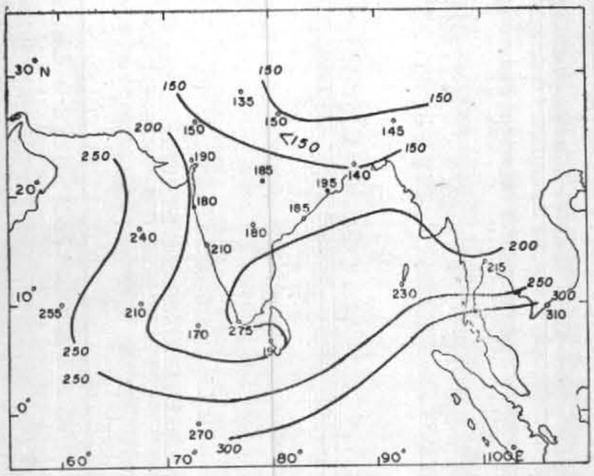

Fig. 3. Estimated heights of *Cb* top (mb) during active monsoon

3.4. *Equivalent potential temperature*

The equivalent potential temperature (θ_e) distribution for active and weak monsoon days at selected stations are plotted in Fig. 2. All these curves show the following features :

(*i*) At all the stations, θ_e values decrease with height, reach a minimum near about 600-700 mb and once again increase with height.

(*ii*) θ_e values during active monsoon are higher than in the weak monsoon. The maximum difference in θ_e between active and weak monsoon occurs at some level between 750 mb and 400 mb, the level varying from station to station.

(*iii*) Convective instability is present in the lower troposphere on all the days; this has been pointed out long ago by Normand and Rao (1946). The convective instability is even slightly more during weak monsoon than active monsoon. Atmosphere tends towards more neutral stability during active monsoon conditions. θ_e profiles are sharper during weak monsoon than during active monsoon.

(*iv*) The minimum values of θ_e (in weak monsoon) vary from 327° A at Minicoy to 343° A at Gauhati. The highest minimum values are over northeast India, east Uttar Pradesh and east Madhya Pradesh. The higher θ_e values over these areas are due to the higher temperatures and the higher moisture content.

4. Heights of tops of *Cb* clouds during active monsoon

If we assume that, during active monsoon, the air near the ground ascends saturated adiabatically with the mean θ_e value between surface and 850 mb level, θ_e will be conserved and the line of this constant θ_e will represent the ascent of such a parcel; the level where this line cuts the environmental θ_e distribution curve, will give the maximum height to which undiluted *Cb* towers can grow. The estimated tops of *Cb* clouds thus obtained are given in Fig. 3. The highest tops are found in the Gangetic Plains—corresponding to the region of low level seasonal monsoon trough and here the values reach about 130-150 mb; this is only slightly below the tropopause levels there, which is near about 100 mb level. Utilising satellite radiation data, Srinivasan (1971) estimated the tops of clouds in active monsoon areas as 12 km (about 200 mb). Analysing the reconnaissance flight reports, Deshpande (1964) showed that, in July and August, the majority of *Cb* tops reach 40000-47500 ft (200-150 mb levels) in India. The heights of *Cb* tops obtained from the θ_e analysis now are generally consistent with these studies. The relatively higher tops in southeast Arabian Sea is an interesting feature.

5. Total Energy

The total energy E of an air column between pressure level p_0 and p is given by $E = \int_{p_0}^{p} Q dp$ where $Q = c_p T + L_q + gz$. Since the vertical distribution of θ_e is similar to that of Q, $\int_{p_0}^{p} \theta_e \, dp$ provides a qualitative measure of E and its variations. The values of this integral were obtained for the various stations by planimetering from the θ_e profiles, and are shown in Figs. 4(a) and 4 (b) for active and weak monsoon situations.

We will examine the two aspects of the total energy, *viz.*, (*i*) Areas having the highest total energy associated with active monsoon and (*ii*) Changes in the total energy content of the air as the monsoon becomes active in the different parts of the country.

Figs. 4(a) and 4 (b) show that the maximum energy in active as well and in weak monsoon is over the Gangetic Plains (or perhaps further north over Tibet) and decreases as we go southwards. The energy is more during active monsoon, principally due to the increase in moisture content. The changes in the total energy between active and weak monsoon is a minimum over northeast India, Uttar Pradesh and Madhya Pradesh. The

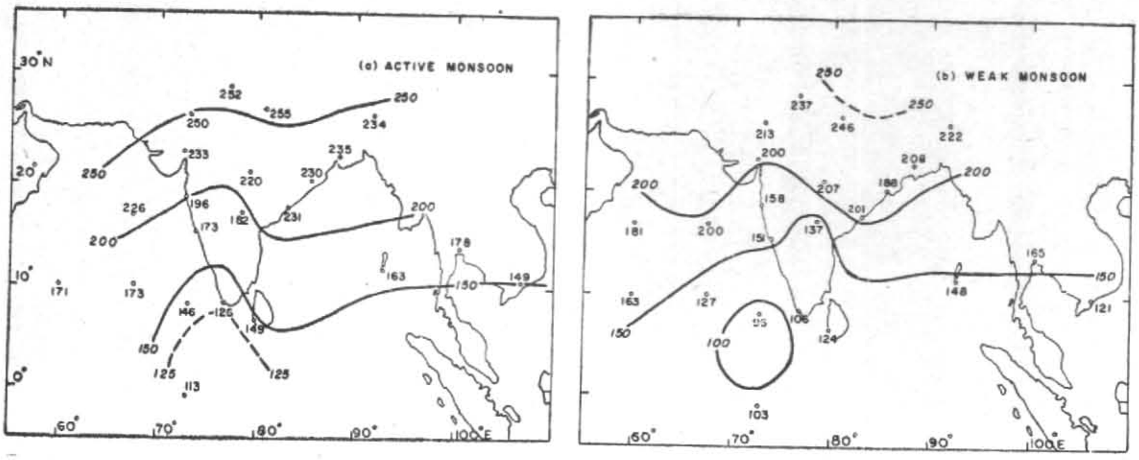

Fig. 4. Total energy (arbitrary units)

TABLE 5

Difference in mean virtual temperatures (°C) during active and weak monsoon

	Pressure levels (mb)											
	SFC/ 1000	900	850	800	700	600	500	400	300	200	150	100
					Jodhpur—Ahmedabad							
$J_a—A_a$	1·3	2·8	2·7	3·5	2·3	0·9	0·4	0·6	0·3	1·5	0	0
$J_w—A_w$	0·6	2·0	3·2	3·4	0·7	0·9	0·8	0·4	1·0	0·2	0·9	0
$J_a—A_w$	0·3	2·3	3·3	3·4	1·6	1·4	0·7	1·0	1·1	1·4	—0·3	0·7
$J_w—A_a$	1·6	2·5	2·6	3·5	1·4	0·4	0·5	0	0·2	0·1	1·2	0·7
					Jodhpur—Bombay							
$J_a—B_a$	1·5	3·3	3·3	3·7	2·9	1·9	1·0	2·5	2·6	3·2	1·7	0·5
$J_w—B_w$	0·9	3·3	3·9	4·9	2·6	2·1	1·9	2·5	3·9	2·9	3·5	0·2
$J_a—B_w$	0·6	3·6	4·0	4·9	3·5	2·6	1·8	3·1	4·0	4·3	2·3	2·9
$J_w—B_a$	1·8	3·0	3·2	3·7	2·0	1·4	1·1	1·9	2·5	1·8	2·9	—0·2

J—Jodhpur, A—Ahmedabad, B—Bombay Subscript 'a' denotes active monsoon and 'w' denotes weak monsoon

maximum changes in the energy occurs at all the stations in the levels between 400 and 800 mb.

6. Comparison with other similar studies

Works of Williams (1970) and Gray (1970) have already been referred to in Sec. 3. Riehl and Malkus (1958) have given the mean distribution of Q in the equatorial trough zone for ocean and land. From the values of Q at the various levels given by Riehl and Malkus the corresponding θ_e distributions were computed and compared with the the θ_e distribution for the Indian stations during the monsoon. It was found that θ_e values over India are much higher than the θ_e values obtained by them; only the weak monsoon curves at Minicoy and Trivandrum have the magnitude of values in the equatorial trough given by Riehl and Malkus. Thus the total energy content in the monsoon trough is very much more than in the mean global equatorial trough (*see* Anjaneyulu 1969).

In the studies in other parts of the world, it has been mentioned (Young 1972) that the decrease in the rate of change of θ_e with height during disturbed weather is brought about (*i*) in the case of oceanic stations, by the increase of θ_e in the mid-tropospheric levels and (*ii*) in the case of land stations by the decrease of θ_e in the lower troposphere. In our studies with Indian data, we do not find any such difference between land and oceanic stations. In both cases, the decrease in rate of changes of θ_e is only due to an increase in θ_e near mid-tropospheric levels.

It is mentioned in earlier literature (for instance, Sawyer 1947) that the temperature gradient over northwest India during the monsoon months, changes sign near about the middle troposphere leading to the so called 'nose' like structure of ITF. Koteswaram (1958) pointed out that this concept is not borne out by later observations and the sub-tropical ridge is warm at all levels and the reversal of horizontal temperature gradient occurs only above the level of the wind maximum (jet). The present study confirms Koteswaram's point as will be seen from Table 5, wherein the differences in virtual temperatures between Jodhpur and Ahmedabad and Jodhpur and Bombay in all possible combinations of monsoon activity have been tabulated. The table shows that, under no circumstance, the density (virtual temperature) gradient changes sign and the northern part always remains warmer (higher virtual temperature) at all the levels in the troposphere. There is no evidence of the folded structure of the density discontinuity postulated earlier.

7. Conclusions

This study has brought out the following results :

(*i*) There is no significant change in the dry bulb temperatures over the Southwest Monsoon area, whatever may be monsoon activity; the main changes are in the dew point temperatures. A similar conclusion has been arrived at by Harris and Ho (1969) in their study with the data of Saigon. The implications of this result have a great significance in the vertical circulations and radiation budget in the tropics as postulated by Gray (1970).

(*ii*) Irrespective of the activity of the monsoon, the moisture content of the atmosphere over the country is quite high (upto 850-600 mb) during the southwest monsoon period.

(*iii*) During active monsoon, synoptic disturbance, pump up the low level moisture and the atmosphere is highly moist from the surface to very high levels.

(*iv*) The Gangetic Plains and the adjoining areas over which the seasonal monsoon trough lies have many significant properties :

(*a*) It is the area where the total energy is a maximum both in active and weak monsoon; the energy change between active and weak monsoon is a minimum here.

(*b*) Undiluted *Cb* tops can reach the maximum heights here.

(*c*) Moisture reaches the maximum heights in the eastern half of the seasonal monsoon trough during active as well as weak monsoon conditions.

(*d*) Convective instability is present upto greater heights in this area than elsewhere over the country.

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