

Climatological studies of lapse rates during summer months vis-à-vis All India Summer Monsoon Rainfall

U. R. JOSHI, G. S. PRAKASA RAO and SHRAVAN KUMAR

India Meteorological Department, Pune - 411 005, India

(Received 19 July 2005, Modified 12 February 2007)

e mail : urjoshi@imd pune.gov.in

सार – इस षोध-पत्र में मानक स्तरों के लिए ग्रीष्मकालीन महीनों (मार्च से मई) के दौरान वर्ष 1971-99 की अवधि पर आधारित 35 रेडियोसौन्दे (आर. एस.) केंद्रों के लिए 0000 और 1200 यू. टी. सी. के लिए मिश्रित औसत सामान्य ह्रास दर तैयार किए गए और उनका विप्लेषण किया गया है। ग्रीष्मकालीन ह्रास दरों और अखिल भारतीय ग्रीष्मकालीन मानसून की वर्षा (जून से सितम्बर) के वितरण के मध्य विद्यमान किसी भी प्रकार के संबंध का पता लगाने के लिए उसी अवधि के तीन अच्छे मानसून वर्षा वाले वर्षों और 6 कम मानसून वर्षा वाले वर्षों के लिए औसत ह्रास दर अलग से तैयार किए गए और ह्रास दर की विसंगतियों (एल. आर. ए.) की विस्तार से जाँच की गई है। अत्याधिक मानसून वर्षा के वर्षों में ह्रास दर की विसंगतियाँ निम्न और मध्य क्षोभमंडल में ग्रीष्मकालीन महीनों (मार्च-मई) के दौरान सामान्यतः धनात्मक (अस्थिर वायुमंडल) थीं और ऊपरी क्षोभमंडल में ये विसंगतियाँ ऋणात्मक थीं। कम मानसून वर्षा वाले वर्षों में यह स्थिति प्रतिकूल रही अर्थात् ह्रास दर की विसंगतियाँ निम्न क्षोभमंडल (संवहनी गतिविधि के अंतर्धी) में धनात्मक थीं जबकि मध्य और ऊपरी क्षोभमंडल में ये विसंगतियाँ ऋणात्मक थीं। इसी प्रकार के परिणाम हाल ही के सबसे खराब मानसून वर्षा वाले वर्ष 2002 और खराब मानसून वर्षा वाले वर्ष 2004 में देखे गए हैं।

इस प्रकार से ह्रास दर की विसंगतियाँ मार्च से मई के महीनों में आगामी अच्छी मानसून वर्षा की सूचना देती हैं और इनका उपयोग दीर्घावधि पूर्वानुमान के लिए एक साधन के रूप में किया जा सकता है।

ABSTRACT. The combined mean normal lapse rates for 0000 and 1200 UTC for 35 Radiosonde (RS) stations based on the period 1971-99 during the summer months (March to May) were worked out for standard levels and analysed. To know whether any relationship exists between the distribution of summer lapse rates and the all India summer monsoon rainfall (June to September), the mean lapse rates for three good monsoon years and six deficient years during the same period were worked out separately and the Lapse Rate Anomalies (LRAs) were examined in detail. In excessive monsoon rainfall years the LRAs were generally negative (instable atmosphere) during summer months (March-May) in the lower and middle troposphere and the anomalies were positive in the upper troposphere. In the deficient monsoon years, the case is reverse *i.e.*, LRAs were positive in the lower troposphere (inhibiting the convective activity) while they were negative in the middle and upper troposphere. The same results were noticed in the recent worst monsoon year 2002 and bad monsoon year 2004.

The LRAs thus give signals in the months of March to May regarding the ensuing monsoon rainfall qualitatively and can be used as one of the tools for long range forecasting.

Key words – Lapse rate anomaly, Upper air temperature, Monsoon rainfall, Instability.

1. Introduction

Lapse rate analysis of temperature is of great importance in the studies of instability of the atmosphere. Large scale stability is one of the major features that strongly influences the dynamics of the atmospheric circulation. Analysis shows that modest spatial/temporal variation in the static stability may have significant dynamical implications upon the disturbances associated

with process of local baroclinic instability (Frederiksen and Frederiksen 1992, Mak 1993). Climatological studies of the stability have shown that tropospheric stability is not temporally and spatially homogeneous (Gates 1961; Lee and Mak 1994). Relatively little study has been done on the lapse rates over the Indian region.

The present study consists of two parts. In the first part the monthly (March, April, May) normal lapse rates

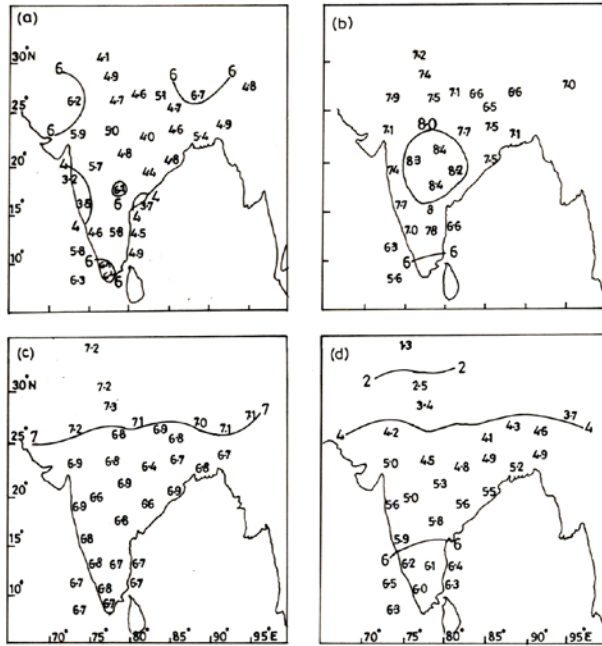
TABLE 1
Mean monthly normal lapse rates (combined 0000 & 1200 UTC)

Station	Ht. (msl)	Lat.	Long.	Normal lapse rate (0000 + 1200) UTC																	
				March						April						May					
				Sur- 850	850- 700	700- 500	500- 300	300- 200	200- 100	Sur- 850	850- 700	700- 500	500- 300	300- 200	200- 100	Sur- 850	850- 700	700- 500	500- 300	300- 200	200- 100
Agartala (21)	16	23.88	91.25	4.9	6.7	5.9	6.7	6.3	4.9	4.6	7.0	6.1	6.6	6.8	5.0	4.5	6.3	5.7	6.1	7.5	6.1
Ahmedabad (29)	55	23.07	72.63	5.9	7.1	6.4	6.9	6.5	5.0	6.1	8.0	6.7	7.0	6.5	5.1	6.2	7.9	6.6	6.5	7.0	5.8
Amini (22)	4	11.12	72.73	5.8	6.3	5.5	6.7	8.1	6.5	5.8	6.3	5.6	6.6	7.9	6.5	6.7	5.7	5.8	6.4	8.1	6.6
Aurangabad (20)	579	19.85	75.40	5.7	8.3	6.2	6.6	6.9	5.0	5.9	8.5	6.8	6.6	6.8	5.0	6.4	8.1	6.6	6.3	7.3	5.6
Bangalore (24)	921	12.97	77.58	5.8	7.8	5.6	6.7	7.8	6.1	6.9	7.5	5.9	6.6	7.8	6.3	6.2	6.9	6.0	6.4	7.9	6.6
Bhopal (17)	523	23.28	77.35	5.0	8.0	6.4	6.8	6.4	4.5	5.3	8.7	7.1	6.7	6.3	4.9	6.1	8.5	7.1	6.2	6.9	5.7
Bhubaneswar (28)	46	20.25	85.25	4.8	7.5	6.0	6.9	7.0	5.5	4.0	7.9	6.5	6.7	7.2	5.8	4.0	7.4	6.4	6.3	7.7	6.4
Cochin (29)	3	9.95	76.27	6.1	6.0	5.5	6.8	8.1	6.0	6.2	5.8	5.6	6.7	8.1	6.3	6.2	5.4	5.6	6.5	8.2	6.5
Dibrugarh (21)	111	27.48	95.02	4.8	7.0	5.6	7.1	5.4	3.7	4.7	6.5	5.8	6.9	6.3	4.2	4.8	6.1	5.5	6.4	7.2	5.6
Goa/Panjim (28)	60	15.48	73.82	3.5	7.7	5.8	6.8	7.7	5.9	3.6	7.3	6.1	6.8	7.6	6.1	5.3	6.0	6.2	6.4	7.9	6.4
Gorakhpur (19)	77	26.75	83.37	5.1	6.6	6.7	6.9	5.6	4.0	5.0	7.6	7.0	7.1	5.8	4.2	5.3	7.2	6.6	6.4	6.5	5.3
Guwahati (29)	54	26.10	91.58	4.9	7.1	5.7	7.1	5.8	4.6	4.9	6.8	5.9	7.1	6.4	4.8	5.2	6.2	5.5	6.4	7.3	5.9
Gwalior (21)	207	26.23	78.25	4.7	7.5	6.5	6.8	5.7	4.0	5.0	8.6	7.0	7.0	5.8	4.2	5.9	8.7	7.1	6.4	6.5	5.2
Hyderabad (28)	545	17.45	78.47	6.1	8.4	6.0	6.8	7.4	5.8	6.5	8.5	6.5	6.6	7.5	6.0	7.4	8.1	6.6	6.3	7.8	6.5
Jagdalpur (20)	553	19.08	82.03	4.4	8.2	5.8	6.6	7.2	5.6	4.5	8.2	6.4	6.5	7.3	5.8	4.2	7.7	6.5	6.0	7.7	6.4
Jodhpur (29)	224	26.30	73.02	6.2	7.9	6.7	7.2	5.8	4.2	6.4	8.7	7.1	7.3	6.0	4.3	6.5	8.3	7.4	6.9	6.5	5.2
Karaikal (21)	7	10.92	79.83	4.9	6.1	5.6	6.7	8.1	6.3	5.2	6.4	5.8	6.6	8.1	6.5	5.2	6.5	5.9	6.4	8.2	6.7
Kolkata (29)	6	22.65	88.45	5.4	7.1	6.2	6.8	6.7	5.2	4.8	7.7	6.5	6.8	7.0	5.5	4.7	7.1	6.1	6.3	7.7	6.4
Lucknow (29)	128	26.75	80.88	4.6	7.1	6.8	7.1	5.5	4.1	4.9	8.2	7.2	7.2	5.8	4.4	5.3	8.1	7.0	6.6	6.7	5.6
Machilipatnam (17)	3	16.20	81.15	3.7	7.2	5.7	6.7	7.3	5.6	3.7	7.3	6.1	6.5	7.5	5.7	4.1	7.1	6.3	6.2	7.6	6.2
Madras (29)	16	13.00	80.18	4.5	6.6	5.6	6.7	7.8	6.4	4.7	6.8	5.9	6.6	7.8	6.6	5.1	7.0	6.1	6.4	7.9	6.7
Mangalore (25)	31	12.95	74.83	4.6	7.0	5.6	6.8	7.9	6.2	5.1	6.6	5.8	6.7	7.9	6.4	5.7	5.7	5.9	6.4	8.0	6.8
Minicoy (29)	2	8.30	73.15	6.3	5.6	5.6	6.7	8.2	6.3	6.3	5.7	5.6	6.7	8.1	6.7	6.6	5.6	5.6	6.5	8.2	6.7
Mumbai (29)	14	19.12	72.85	3.2	7.4	6.4	6.9	7.2	5.6	3.3	7.3	6.7	7.0	7.2	5.7	4.5	6.4	6.6	6.6	7.6	6.3
Nagpur (29)	310	21.10	79.05	4.8	8.4	6.4	6.9	6.8	5.3	5.4	8.8	7.1	6.7	6.9	5.4	6.0	8.7	7.2	6.2	7.3	6.3
New Delhi (29)	216	28.58	77.20	4.9	7.4	6.9	7.3	5.2	3.4	5.7	8.4	7.2	7.4	5.6	3.8	5.7	8.5	7.3	6.8	6.3	5.0
Patiala (22)	251	30.33	76.47	4.1	7.2	6.9	7.2	4.9	2.5	4.4	8.0	7.2	7.3	5.5	3.0	5.1	8.1	7.3	6.7	5.9	4.1
Patna (16)	60	25.60	85.10	4.7	6.5	6.4	6.8	5.8	4.1	4.9	7.9	6.7	6.8	6.1	4.7	5.2	7.3	6.3	6.1	6.8	5.8
Pendra (14)	625	22.77	81.90	4.0	7.7	6.2	6.4	6.6	4.8	4.8	8.4	7.2	6.4	6.7	5.0	4.7	8.2	7.0	5.9	7.1	5.6
Port Blair (29)	79	11.67	92.72	5.3	5.6	5.5	6.7	8.2	6.4	5.7	5.8	5.5	6.6	8.2	6.6	5.8	5.4	5.5	6.4	8.3	6.8
Ranchi (22)	606	23.43	85.40	4.6	7.5	6.2	6.7	6.4	4.9	4.5	8.4	6.9	6.6	6.6	5.0	4.6	8.0	6.6	6.1	7.3	6.1
Siliguri (16)	123	26.67	88.37	6.7	6.6	6.0	7.0	5.6	4.3	6.5	6.6	6.3	7.0	6.0	4.3	6.2	6.0	5.8	6.5	6.9	5.6
Srinagar (29)	1587	34.08	74.83			6.8	7.2	4.4	1.3			7.1	7.4	5.5	1.8			7.1	7.1	5.5	3.1
Thiruvananthapuram (29)	64	8.48	76.95	6.4	5.4	5.6	6.7	8.1	6.4	6.1	5.5	5.7	6.7	8.1	6.6	6.0	5.3	5.7	6.5	8.2	6.7
Visakhapatnam (29)	3	17.72	83.23	4.3	7.5	5.7	6.7	7.3	6.0	3.7	7.7	6.3	6.5	7.5	6.3	4.1	7.2	6.4	6.2	7.8	6.8

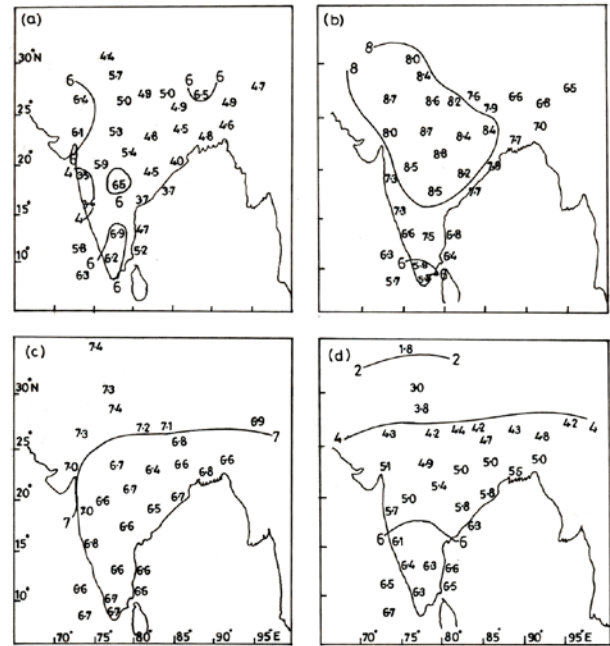
Figures in the bracket against station name indicate the number of years of data considered

based on 0000 & 1200 UTC radiosonde ascents (35 stations) for the period 1971-99 were worked out. The lapse rates were worked out for six layers, *i.e.*, (i) Surface – 850 hPa (ii) 850-700 hPa (iii) 700-500 hPa (iv) 500-300 hPa (v) 300-200 hPa and (vi) 200-100 hPa and were analysed. In the second part combined (0000 and 1200 UTC) lapse rates were worked out for the same months for excessive and deficient monsoon years separately for the above six layers. Following the departmental criteria,

a year was classified as deficient monsoon rainfall year where all India rainfall is < 10% of long period average rainfall (LPA). Similarly, a year was classified as excessive rainfall year when all India rainfall was >10% LPA. During the period of study there were six deficient rainfall years 1972, 1974, 1979, 1982, 1986, 1987 and three excessive rainfall years 1975, 1988 and 1994. As the absolute lapse rates may not throw any light on the ensuing monsoon conditions, the lapse rate anomalies



Figs. 1(a-d). Normal lapse rate ($^{\circ}\text{C}/\text{km}$) for March (a) Surface - 850 hPa, (b) 850 - 700 hPa, (c) 500 - 300 hPa and (d) 200 - 100 hPa



Figs. 2(a-d). Normal lapse rate ($^{\circ}\text{C}/\text{km}$) for April (a) Surface - 850 hPa, (b) 850 - 700 hPa, (c) 500 - 300 hPa and (d) 200 - 100 hPa

(LRAs), *i.e.*, actual lapse rate minus normal lapse rate were worked out for excessive and deficient years and the results were discussed. Rajeevan (1991) calculated the thermal anomalies using vector wind shear and concluded that during drought years, for the month of April the whole troposphere (850-200 hPa) over NW India was cooler and it was warmer during flood years, while the present study was based on the actual temperature values of the troposphere.

2. Data and methodology

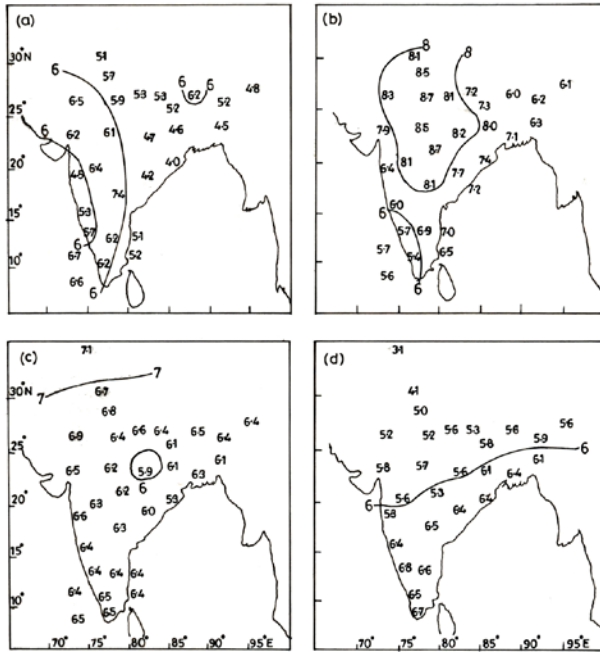
2.1. Normal lapse rates

The monthly means of upper air data for 35 radiosonde stations for the period 1971-99 were obtained from the National Data Centre (NDC) and the lapse rates were worked from surface to 100 hPa for six layers. Prior to 1968-69 different types of radiosonde instruments were in operation. Since 1969 the same type of audio modulated radiosonde instruments manufactured and calibrated at the instruments division of the IMD were in operation at all the stations (Ananthkrishnan and Soman, 1989). Hence the radiosonde data from 1971 were considered for preparation of normal values. The mean normal lapse rates obtained for 0000 and 1200 UTC for the summer months (March-May) were given in Table 1. The data for all the 35 stations were not available in the initial years and the Figures in the brackets by the side of the station name indicate the number of years

of data considered. The mean normal lapse rates for Surface - 850 hPa, 850-700 hPa (lower troposphere), 500-300 hPa (middle troposphere) and 200-100 hPa (upper troposphere) for the months of March-May were also shown diagrammatically in Figs. 1 to 3.

During March in the lower troposphere from surface to 850 hPa Fig. 1(a), it was seen that lapse rate values range from 4.1 to 5.9 $^{\circ}\text{C}/\text{km}$ with higher values of 6 $^{\circ}\text{C}/\text{km}$ and above over NW India and SW tip of peninsula and at Hyderabad and Dibrugarh. At 850-700 hPa the lapse rates were of the order 8 $^{\circ}\text{C}/\text{km}$ in north peninsula and adjoining central parts of India [Fig 1(b)]. They were decreasing either side reaching a low value of 5.4 $^{\circ}\text{C}/\text{km}$ towards the extreme south peninsula. In the middle troposphere Fig. 1(c) the lapse rates were of the order of 6.4 to 7.3 $^{\circ}\text{C}/\text{km}$ with a flat gradient. In the upper troposphere Fig. 1(d) the gradient was from south to north with high values (6.4 $^{\circ}\text{C}/\text{km}$) over the extreme south peninsula and low value at Srinagar (1.3 $^{\circ}\text{C}/\text{km}$).

As the season progresses, in April in the lower troposphere, Surface - 850 hPa Fig. 2(a), the lapse rates were similar to the March values with an additional high value of 6.9 $^{\circ}\text{C}/\text{km}$ at Bangalore. At 850 - 700 hPa Fig. 2(b) the lapse rates were of the order of 8.2 to 8.8 $^{\circ}\text{C}/\text{km}$ over north peninsula, central, north and northwest India. The lowest value of 5.5 $^{\circ}\text{C}/\text{km}$ was reported at the extreme south peninsula. In the middle troposphere, Fig. 2(c) they were of the order of 7.4



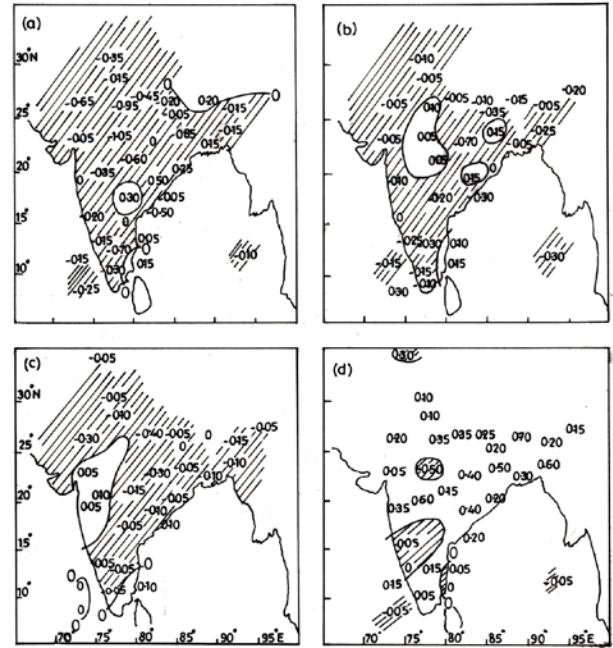
Figs. 3(a-d). Normal lapse rate ($^{\circ}\text{C}/\text{km}$) for May (a) Sur-850 hPa, (b) 850 - 700 hPa, (c) 500 - 300 hPa and (d) 200 - 100 hPa

to $6.7^{\circ}\text{C}/\text{km}$ decreasing from north to south. In the upper troposphere Fig. 2(d) the lapse rate values decrease from $6.6^{\circ}\text{C}/\text{km}$ (Thiruvananthapuram) to $1.8^{\circ}\text{C}/\text{km}$ (Srinagar) with a south-north gradient.

During May in the lower troposphere, Surface 850 hPa [Fig. 3(a)] the lapse rates were decreasing from west to east from 6.5 to $4.8^{\circ}\text{C}/\text{km}$ excluding the west coast stations of Mumbai, Panjim and Mangalore where they were less than $6^{\circ}\text{C}/\text{km}$. Hyderabad had the highest value of $7.4^{\circ}\text{C}/\text{km}$. The lapse rates in the layer 850-700 hPa Fig. 3(b) were same as in April with the exception that $6^{\circ}\text{C}/\text{km}$ isoline extended from southern tip of peninsula to Goa along the west coast. In the middle troposphere [Fig. 3(c)] they were of the order of 6.1 to $6.5^{\circ}\text{C}/\text{km}$ over the entire country (with a very flat gradient) except Srinagar ($7.1^{\circ}\text{C}/\text{km}$). In the upper troposphere [Fig. 3(d)] the lapse rates were decreasing from south to north from 6.7 to $3.1^{\circ}\text{C}/\text{km}$.

2.2. Deficient and excessive monsoon years

In the second part, the lapse rates were worked out separately for the summer season (March to May) of excessive and deficient monsoon years from surface to 100 hPa for the combined hours of observations (*i.e.*, 0000 & 1200 UTC). In the surface to 850 hPa layer there may be inversions present, but during this season they were practically absent and not considered while working out the lapse rates.



Figs. 4(a-d). Average lapse rate anomaly ($^{\circ}\text{C}/\text{km}$) 0000 & 1200 UTC for March (excess rainfall years). Shaded portions indicate the negative values (a) Sur - 850 hPa, (b) 850 - 700 hPa, (c) 500 - 300 hPa and (d) 200 - 100 hPa

From these lapse rates the anomalies (actual lapse rate – normal lapse rate) were worked out for excess and deficient rainfall years and presented in Tables 2 and 3 respectively.

3. Analysis and discussions

3.1. Excess rainfall years (1975, 1988 and 1994)

The lapse rate anomaly charts were analysed for all the six layers for the months March-May. However, charts representing Surface - 850 hPa, 850 - 700 hPa, 500 - 300 hPa and 200 - 100 hPa were presented diagrammatically in Figs 4 to 6 representing lower, middle and upper troposphere.

3.1.1. March

Surface to 850 hPa – The LRAs were negative throughout the country except for isolated pockets over Siliguri, Dibrugarh and Hyderabad [Fig 4(a)].

850-700 hPa – The LRAs were negative throughout the country except for a small area over parts of west M.P., Orissa and Ranchi [Fig. 4(b)].

700-500 hPa – The LRAs were negative over the country except over parts of west Madhya Pradesh and U.P. and along latitudinal belt of 13°N .

TABLE 2

Lapse rate anomaly values (excess rainfall years)

Station	Lapse rates anomaly (0000 + 1200) UTC																	
	March						April						May					
	Sur-850	850-700	700-500	500-300	300-200	200-100	Sur-850	850-700	700-500	500-300	300-200	200-100	Sur-850	850-700	700-500	500-300	300-200	200-100
Agartala	-0.15	-0.25	-0.30	-0.10	0.10	0.60	-0.15	-0.15	0.00	-0.05	0.05	0.15	-0.15	-0.65	-0.15	-0.20	0.10	0.45
Ahmedabad	-0.05	-0.05	0.00	0.05	0.20	0.05	0.20	0.10	0.05	0.05	-0.30	-0.20	0.05	-0.35	0.05	0.05	-0.05	0.25
Amini	-0.15	-0.15	0.00	0.10	0.15	0.15	-0.70	-0.05	-0.05	0.15	0.05	1.05	-0.50	-0.50	0.30	-0.05	-0.05	0.90
Aurangabad	-0.35	0.00	-0.30	0.10	0.15	0.50	0.55	-0.70	-0.30	-0.05	-0.65	0.10	-0.85	-0.55	-0.15	-0.20	-0.10	0.20
Bangalore	-0.70	-0.30	0.00	-0.05	0.00	0.15	-0.45	-0.50	-0.10	-0.05	-0.25	-0.25	-0.70	-0.45	0.30	-0.30	-0.20	0.10
Bhopal	-1.05	0.05	0.20	0.00	0.20	-0.50	-0.70	-0.05	0.30	0.05	-0.45	-0.40	-1.25	0.10	0.20	-0.20	0.10	0.50
Bhubaneswar	0.25	0.00	-0.25	0.05	0.30	0.20	-0.05	-0.20	-0.25	0.35	-0.05	-0.20	-0.15	-0.10	-0.05	-0.10	0.10	0.35
Chennai	-0.05	0.10	0.00	0.00	0.05	-0.05	0.30	-0.40	-0.05	0.05	0.05	-0.30	0.00	-0.15	0.15	-0.15	-0.10	0.05
Cochin	-0.30	-0.15	-0.05	-0.05	0.10	0.05	-0.45	-0.10	-0.10	-0.05	-0.20	-0.10	-0.35	-0.30	0.10	-0.20	-0.30	0.05
Dibrugarh	0.00	-0.20	-0.10	-0.05	0.15	0.15	-0.10	-0.10	-0.05	0.05	-0.10	0.10	0.15	-0.05	-0.05	-0.40	0.00	0.85
Goa/Panjim	-0.20	0.00	0.00	0.00	0.25	-0.05	0.30	0.10	0.05	0.05	-0.05	-0.15	0.55	-0.50	0.25	-0.10	-0.20	0.30
Gorakhpur	-0.20	-0.10	0.20	-0.05	0.20	0.25	-0.45	0.10	0.30	-0.15	-0.30	-0.15	-0.05	-0.05	0.05	-0.10	-0.10	0.75
Guwahati	-0.15	-0.05	-0.10	-0.15	0.10	0.20	-0.45	0.10	0.05	0.05	-0.10	-0.15	-0.65	-0.10	0.00	-0.20	-0.10	0.30
Gwalior	-0.95	0.10	0.10	0.10	0.65	0.35	-0.55	-0.10	0.15	0.00	-0.30	-0.05	-0.25	-0.25	0.20	-0.30	-0.05	0.80
Hyderabad	0.30	-0.20	-0.05	-0.05	0.25	-0.05	-0.20	-0.45	-0.15	0.05	-0.15	-0.15	0.25	0.25	0.20	-0.10	-0.20	0.00
Jagdapur	-0.50	0.15	-0.20	0.10	0.10	0.40	0.15	-0.25	-0.05	0.05	-0.45	-0.10	-0.80	0.00	0.10	-0.10	-0.15	0.30
Jodhpur	-0.65	-0.05	-0.10	-0.30	0.45	0.20	-0.35	-0.10	0.15	0.20	-0.30	-0.60	-0.55	-0.20	0.10	-0.25	0.10	0.40
Karaikal	0.15	0.15	-0.05	0.10	0.00	0.00	0.25	-0.50	-0.05	0.05	0.00	0.00	0.00	-0.10	0.15	0.00	0.10	0.00
Kolkata	-0.15	-0.05	-0.15	-0.10	0.45	0.30	-0.50	-0.15	0.00	0.15	0.25	0.05	-0.10	-0.25	-0.15	-0.30	0.05	0.35
Lucknow	-0.45	-0.05	0.10	-0.40	0.40	0.35	-0.35	0.10	0.10	0.00	0.00	-0.10	0.10	-0.20	0.10	-0.35	-0.25	0.35
Machilipatnam	-0.50	-0.05	-0.10	-0.10	0.35	0.20	0.25	-0.60	0.00	0.15	-0.10	0.00	-0.20	-0.25	0.20	-0.15	0.15	0.10
Mangalore	-0.15	-0.25	0.05	-0.05	0.10	0.00	-0.10	-0.30	0.05	0.15	-0.10	-0.05	0.20	-0.55	0.30	-0.10	-0.45	0.20
Minicoy	-0.25	0.30	-0.15	0.00	0.10	-0.05	-0.10	-0.10	0.00	0.00	0.00	-0.05	-0.10	-0.15	0.20	-0.05	-0.05	0.00
Mumbai	0.00	-0.10	-0.30	0.05	0.35	0.35	0.00	-0.05	0.05	0.10	-0.15	0.00	-0.15	-0.20	0.05	-0.05	-0.05	0.45
Nagpur	-0.60	0.05	-0.15	-0.15	0.25	0.15	-0.40	-0.30	0.00	-0.05	-0.25	-0.20	-0.25	0.00	0.20	-0.35	0.00	0.45
New Delhi	-0.15	-0.05	0.05	-0.10	0.15	0.10	-0.35	0.10	0.05	0.10	-0.05	-0.50	-0.20	0.05	0.20	-0.20	-0.25	0.45
Patiala	-0.35	-0.10	0.05	-0.05	0.30	0.10	0.15	0.20	0.00	0.25	-0.30	-0.60	-0.15	0.00	0.25	-0.15	-0.40	0.35
Patna	-0.05	-0.35	-0.10	0.00	0.20	0.20	0.05	-0.20	0.00	0.10	-0.35	-0.10	0.05	-0.45	-0.10	-0.40	0.15	0.55
Pendra	0.00	-0.70	-0.60	-0.30	0.45	0.40	-0.30	-0.50	-0.25	0.05	-0.75	-0.30	-0.35	0.00	0.15	-0.60	0.10	0.70
Port Blair	-0.10	-0.30	0.10	-0.05	0.00	-0.05	-0.05	-0.30	0.10	-0.10	-0.25	-0.05	-0.55	-0.05	-0.05	-0.15	-0.20	0.10
Ranchi	-0.85	0.15	-0.05	-0.05	0.25	0.50	-0.50	-0.25	-0.15	-0.15	-0.15	0.05	-0.25	-0.10	-0.10	-0.20	0.15	0.45
Siliguri	0.20	-0.15	-0.30	0.00	0.25	0.70	0.25	0.05	0.10	0.20	0.00	0.40	0.20	0.00	0.00	-0.30	-0.15	1.20
Srinagar			-0.25	-0.05	0.35	-0.30			0.00	-0.15	0.20	-0.95			-0.05	0.00	-0.45	-0.30
Thiruvananthapuram	-0.10	-0.10	0.00	0.05	0.00	0.15	-0.45	-0.20	-0.10	0.05	-0.15	0.10	0.10	-0.25	0.20	-0.05	0.00	0.10
Visakhapatnam	-0.05	-0.30	0.00	-0.10	0.40	0.40	0.20	-0.60	-0.05	0.20	0.10	0.20	0.00	-0.20	0.05	-0.15	-0.05	0.40

500-300 hPa – The LRAs were negative over the country except over extreme southeast Tamil Nadu, parts of Gujarat region and adjoining parts of Maharashtra and Madhya Pradesh [Fig. 4(c)].

300-200 hPa – The LRAs were positive throughout the country.

200-100 hPa – The LRAs were positive throughout the country except isolated pockets over Srinagar, Mangalore, Goa and Hyderabad [Fig. 4(d)].

3.1.2. April

Surface to 850 hPa – The LRAs were negative over the country except over Patiala, coastal Andhra Pradesh

TABLE 3
Lapse rate anomaly (deficient rainfall years)

Station	Lapse rates anomaly (0000 + 1200) UTC																	
	March						April						May					
	Sur-850	850-700	700-500	500-300	300-200	200-100	Sur-850	850-700	700-500	500-300	300-200	200-100	Sur-850	850-700	700-500	500-300	300-200	200-100
Agartala	0.00	0.25	0.00	-0.45	0.30	0.30	0.20	0.00	0.00	0.00	0.00	-0.60	0.30	0.40	-0.10	0.10	0.00	-0.45
Ahmedabad	-0.10	0.05	0.15	0.10	-0.15	0.30	-0.10	0.25	0.00	-0.05	0.35	-0.15	0.00	0.10	-0.15	0.25	0.00	-0.20
Amini	0.45	0.25	-0.25	-0.25	0.15	0.10	-0.05	0.15	-0.05	-0.05	0.15	0.15	0.20	0.40	-0.20	-0.05	0.10	0.10
Aurangabad	0.25	-0.20	-0.20	-0.75	0.05	0.20	0.35	-0.20	-0.30	-0.10	0.45	-0.45	-0.65	-0.10	-0.30	-0.10	-0.30	-0.35
Bangalore	0.80	0.20	0.00	0.05	0.10	0.10	0.65	0.45	-0.10	0.20	0.20	0.00	1.00	0.25	-0.10	0.10	0.25	0.00
Bhopal	0.40	0.15	-0.10	-0.85	-0.15	-0.10	-0.25	0.10	-0.35	0.00	0.50	-0.55	0.05	-0.05	-0.25	-0.10	-0.30	-0.45
Bhubaneswar	0.20	0.15	-0.05	-0.05	-0.10	0.00	0.35	0.15	0.00	0.10	0.00	-0.10	0.90	0.15	-0.15	0.10	0.10	-0.25
Chennai	-0.05	0.10	0.00	0.00	0.10	0.10	0.05	0.25	-0.10	0.20	0.10	0.00	0.35	-0.05	-0.15	0.00	0.10	-0.25
Cochin	0.20	0.15	-0.05	-0.05	0.00	-0.25	0.20	0.05	-0.10	0.10	0.15	-0.10	-0.05	0.10	-0.10	0.00	0.15	-0.40
Dibrugarh	-0.05	0.05	-0.10	-0.25	0.10	0.20	0.15	-0.10	-0.05	0.15	-0.15	-0.25	0.40	0.35	-0.15	0.00	0.25	0.00
Goa/Panjim	0.50	0.20	-0.10	-0.10	0.00	0.00	0.30	0.35	-0.05	0.05	0.25	-0.25	0.25	0.40	-0.15	0.05	0.15	-0.30
Gorakhpur	-0.50	0.40	-0.20	-0.20	-0.25	0.20	-0.35	0.10	-0.20	0.25	0.10	-0.25	-0.10	0.40	0.00	0.10	-0.35	-0.35
Guwahati	-0.10	0.15	0.05	-0.05	-0.30	0.25	-0.05	-0.05	0.00	0.05	-0.15	-0.05	0.35	0.25	0.05	0.15	0.05	-0.15
Gwalior	0.15	0.15	-0.05	-0.15	-0.25	0.25	0.25	0.05	0.10	0.00	0.20	-0.55	0.20	-0.15	-0.25	0.20	0.05	-0.95
Hyderabad	0.45	0.05	-0.05	0.00	0.10	0.25	0.50	0.20	-0.10	0.15	0.15	-0.05	0.15	0.10	-0.25	0.05	0.15	0.05
Jagdarpur	0.65	0.05	-0.20	-0.45	0.00	0.20	0.30	0.00	0.00	0.10	0.25	-0.40	0.30	0.30	-0.10	-0.05	0.15	-0.20
Jodhpur	0.20	-0.15	0.05	0.10	-0.25	0.05	0.35	-0.10	-0.05	-0.10	0.20	-0.10	-0.10	0.15	-0.20	0.00	-0.10	-0.55
Karaikal	0.60	0.00	-0.20	-0.15	0.10	0.15	0.35	0.10	-0.20	0.00	0.20	0.05	0.30	0.20	-0.20	-0.05	0.15	-0.15
Kolkata	0.30	0.15	0.10	0.00	-0.25	0.15	0.25	0.30	-0.05	0.00	0.10	-0.15	0.30	0.55	-0.05	0.05	0.15	-0.20
Lucknow	0.05	0.05	0.00	0.15	-0.25	0.05	0.45	0.20	-0.15	0.05	0.20	-0.10	0.25	0.30	-0.05	0.10	-0.10	-0.50
Machilipatnam	0.10	0.05	-0.50	-0.50	0.10	0.45	-0.40	0.35	-0.35	0.05	0.05	-0.35	0.50	0.20	-0.25	-0.25	0.10	-0.40
Mangalore	0.25	0.30	-0.35	-0.10	0.30	0.45	-0.30	0.55	-0.20	0.20	0.20	-0.10	0.00	0.45	-0.05	0.10	0.20	-0.15
Minicoy	0.25	0.15	-0.15	-0.10	0.00	0.05	0.10	0.20	-0.15	0.00	0.15	0.05	-0.05	0.30	-0.10	-0.05	-0.05	-0.10
Mumbai	-0.20	0.40	0.00	-0.20	0.05	0.05	0.70	0.15	-0.15	-0.10	0.15	-0.20	0.40	0.35	-0.15	0.10	-0.05	-0.25
Nagpur	-0.10	0.15	0.10	-0.05	-0.25	0.05	0.35	0.20	0.00	-0.10	0.25	0.10	0.15	0.10	-0.25	0.15	0.00	-0.30
New Delhi	0.35	-0.05	-0.15	0.10	-0.10	0.15	0.40	0.10	-0.20	-0.10	0.25	0.05	0.60	-0.05	-0.25	0.10	-0.20	-0.40
Patiala	0.20	-0.05	-0.25	0.15	-0.30	0.05	0.65	-0.15	-0.15	0.05	0.20	0.10	0.50	-0.35	-0.20	0.20	-0.05	-0.65
Patna	-0.20	0.30	-0.20	-0.50	-0.10	0.05	-0.40	-0.10	-0.05	0.10	0.15	-0.45	0.00	0.15	0.00	0.00	-0.20	-0.55
Pendra	0.75	-0.20	0.00	-0.20	-0.05	0.05	0.45	0.20	-0.20	0.05	0.00	-0.50	0.60	0.15	-0.30	-0.05	-0.10	-0.30
Port Blair	-0.10	0.00	0.00	0.00	0.10	0.00	0.10	0.05	-0.10	0.00	0.20	0.00	0.10	0.20	-0.05	0.10	0.25	-0.30
Ranchi	-0.25	0.15	-0.10	-0.45	0.00	-0.05	-0.20	0.20	-0.05	0.05	0.10	-0.55	0.65	0.40	-0.20	0.05	0.15	-0.25
Siliguri	-0.15	0.30	-0.20	-0.35	0.15	0.05	-0.90	-0.15	-0.15	0.20	-0.10	-0.50	0.45	0.30	-0.35	-0.10	-0.15	-0.30
Srinagar			-0.20	-0.05	0.35	-0.05			-0.15	0.05	0.30	-0.10			-0.20	0.15	0.20	-0.90
Thiruvananthapuram	0.20	0.00	-0.10	0.00	0.10	-0.20	0.35	0.05	-0.20	0.05	0.05	-0.20	0.15	0.25	-0.25	0.05	0.10	-0.30
Visakhapatnam	0.05	0.30	0.00	-0.15	0.20	0.30	0.25	0.25	0.00	0.05	0.25	-0.25	0.55	0.25	-0.15	0.00	0.20	-0.15

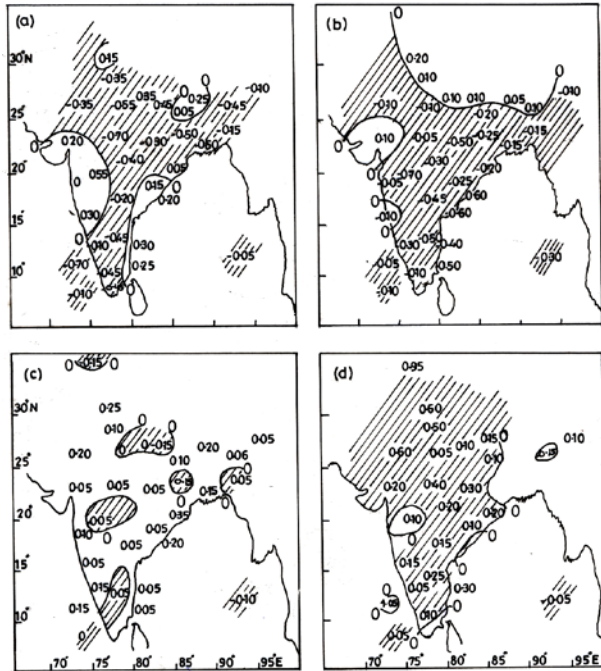
and adjoining coastal Tamil Nadu, Konkan & Goa and parts of Madhya Maharashtra and Gujarat [Fig. 5(a)].

850-700 hPa – The LRAs were negative over the country except along the foot hills of Himalayas, Goa and Gujarat [Fig. 5(b)].

700-500 hPa – The LRAs were negative over Kerala, Tamilnadu, Andhra Pradesh, parts of Maharashtra

& Madhya Pradesh, Orissa, Jharkhand, West Bengal and extreme north eastern parts of India. Elsewhere they were positive.

500-300 hPa – The LRAs were positive over the country except for isolated pockets over Srinagar, regions covering Gwalior, Lucknow, Gorakhpur, Jharkhand, Tripura, Aurangabad, Nagpur, Bangalore and Cochin [Fig. 5(c)].



Figs. 5(a-d). Average lapse rate anomaly ($^{\circ}\text{C}/\text{km}$) 0000 & 1200 UTC for April (excess rainfall years). Shaded portions indicate the negative values (a) Sur - 850 hPa, (b) 850 - 700 hPa, (c) 500 - 300 hPa and (d) 200 - 100 hPa

300-200 hPa – The LRAs were negative over the country except over Srinagar, Kolkata, Agartala, Chennai and Karaikal.

200-100 hPa – The LRAs were negative over the country except over NE India, West Bengal and adjoining parts of Bihar, Aurangabad and Thiruvananthapuram [Fig. 5(d)].

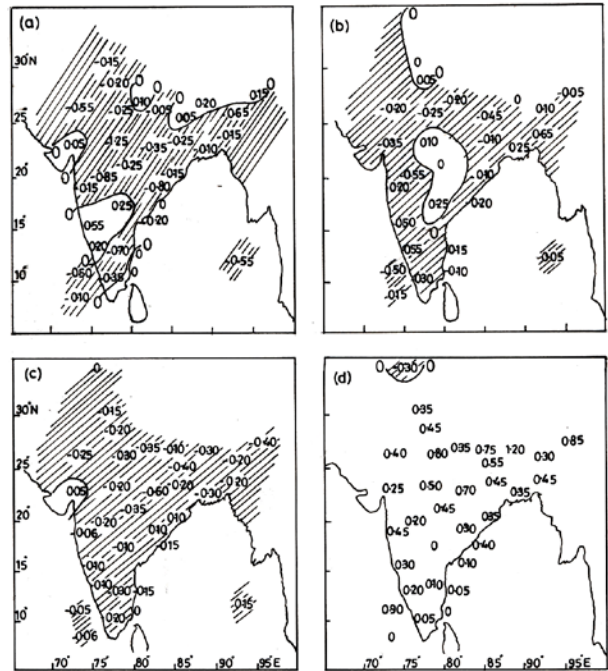
3.1.3. *May*

Surface to 850 hPa – The LRAs were negative over the country except over Gujarat, Patna, Siliguri, Dibrugarh, extreme south peninsula, Telangana, north coastal Karnataka and Goa coasts [Fig. 6(a)].

850-700 hPa – The LRAs were negative over the country except over northern parts of north India and parts of MP and Telangana [Fig. 6(b)].

700-500 hPa – The LRAs were positive over the country except over eastern parts of India.

500-300 hPa – The LRAs were negative over the country except over Gujarat [Fig. 6(c)].



Figs. 6(a-d). Average lapse rate anomaly ($^{\circ}\text{C}/\text{km}$) 0000 & 1200 UTC for May (excess rainfall years). Shaded portions indicate the negative values (a) Sur - 850 hPa, (b) 850 - 700 hPa, (c) 500 - 300 hPa and (d) 200 - 100 hPa

300-200 hPa – The LRAs were negative over the country except over parts of Rajasthan, Madhya Pradesh, Bihar and West Bengal.

200-100 hPa – The LRAs were positive over the country except an isolated pocket over Srinagar [Fig. 6(d)].

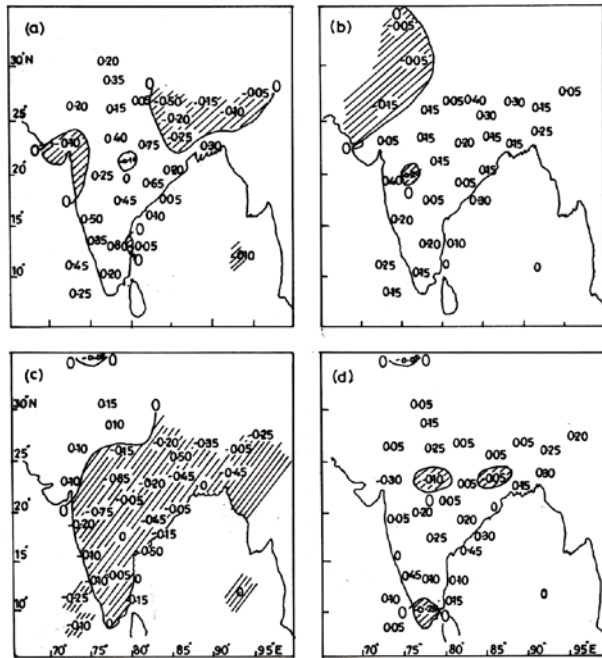
3.2. *Deficient rainfall years (1972, 1974, 1979, 1982, 1986 and 1987)*

The lapse rate anomaly charts were analysed for all the six layers for the months March-May. However, charts representing Surface - 850 hPa, 850 - 700 hPa, 500 - 300 hPa and 200 - 100 hPa were presented diagrammatically in Figs. 7 to 9 representing lower, middle and upper troposphere.

3.2.1. *March*

Surface to 850 hPa – The LRAs were positive over the country except over Ahmedabad, Mumbai, Nagpur, Bihar and NE India [Fig. 7(a)].

850-700 hPa – The LRAs were positive over the country except over parts of NW and North India comprising of Jodhpur, New Delhi, Patiala and Srinagar [Fig.7(b)].



Figs. 7(a-d). Average lapse rate anomaly ($^{\circ}\text{C}/\text{km}$) 0000 & 1200 UTC for March (deficient rainfall years). Shaded portions indicate the negative values (a) Sur - 850 hPa, (b) 850 - 700 hPa, (c) 500 - 300 hPa and (d) 200 - 100 hPa

700-500 hPa – The LRAs were negative over the country except over Jodhpur, Ahmedabad, Mumbai, Nagpur, Kolkata and Guwahati.

500-300 hPa – The LRAs were negative over the country except over Gujarat, Rajasthan, Uttaranchal and north India [Fig.7(c)].

300-200 hPa – The LRAs were negative over the country except over most parts of peninsula south of 20°N , Tripura and Dibrugarh.

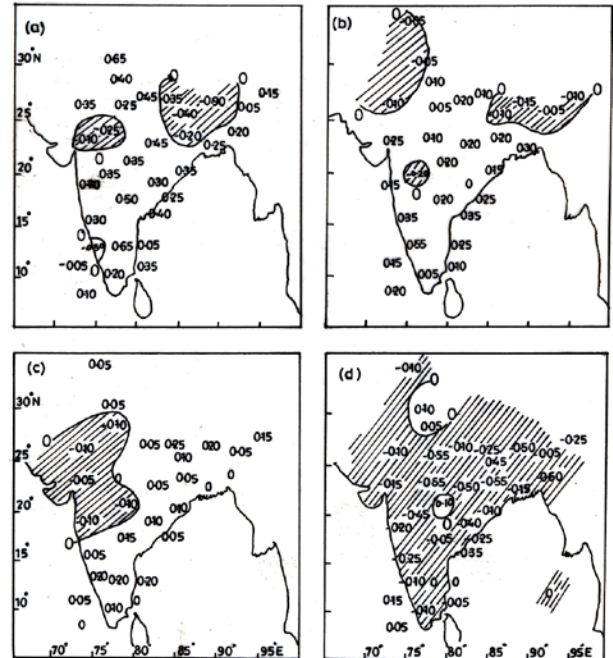
200-100 hPa – The LRAs were positive over the country except over Kochi, Thiruvananthapuram, Bhopal, Ranchi and Sringer [Fig.7(d)].

3.2.2. April

Surface to 850 hPa – The LRAs were positive over the country except over Mangalore, Ahmedabad, Bhopal, parts of east UP, Bihar and Assam [Fig. 8(a)].

850-700 hPa – The LRAs were positive over the country except over Jodhpur, Patiala, Srinagar, parts of Bihar and Assam and Meghalaya [Fig. 8(b)].

700-500 hPa – The LRAs were negative over the country except over Gwalior.



Figs. 8(a-d). Average lapse rate anomaly ($^{\circ}\text{C}/\text{km}$) 0000 & 1200 UTC for April (deficient rainfall years). Shaded portions indicate the negative values (a) Sur - 850 hPa, (b) 850 - 700 hPa, (c) 500 - 300 hPa and (d) 200 - 100 hPa

500-300 hPa – The LRAs were positive over the country except over Rajasthan, Gujarat, parts of Maharashtra and west M.P. and New Delhi [Fig. 8(c)].

300-200 hPa – The LRAs were positive over the country except over NE India.

200-100 hPa – The LRAs were negative over the country except over Nagpur, New Delhi and Patiala [Fig. 8(d)].

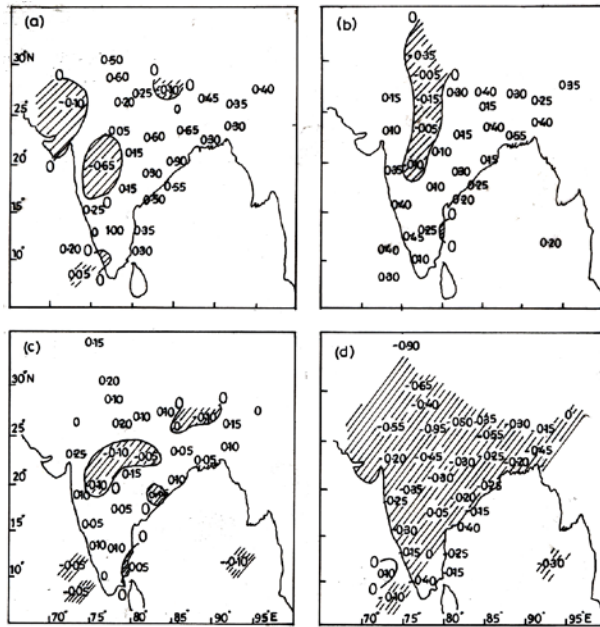
3.2.3. May

Surface to 850 hPa – The LRAs were positive over the country except over Kochi, Aurangabad, Jodhpur and Gorakhpur [Fig. 9(a)].

850-700 hPa – The LRAs were positive over the country except along a tongue extending from north to south over Patiala, New Delhi, Gwalior, Bhopal and Aurangabad [Fig. 9(b)].

700-500 hPa – The LRAs were negative over the country except over Guwahati.

500-300 hPa – The LRAs were positive except over Aurangabad, Bhopal, Pendra, Siliguri, Jagdalpur and Karaikal [Fig. 9(c)].



Figs. 9(a-d). Average lapse rate anomaly ($^{\circ}\text{C}/\text{km}$) 0000 & 1200 UTC for May (deficient rainfall years). Shaded portions indicate the negative values (a) Sur - 850 hPa, (b) 850 - 700 hPa, (c) 500 - 300 hPa and (d) 200 - 100 hPa

300-200 hPa – The LRAs were negative mainly over central India, parts of North India and Bihar. Rest of the country the LRAs are positive.

200-100 hPa – The LRAs were negative over the country except over Hyderabad [Fig. 9(d)].

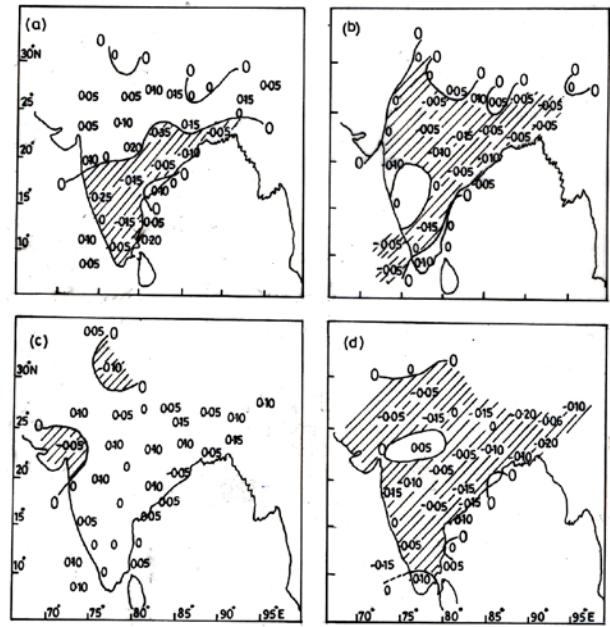
3.3. *Lapse rate anomalies for normal rainfall years*

The lapse rate anomaly charts were also analysed for the 20 normal years for the months March – May. The analysed charts of LRAs for representing Surface – 850 hPa, 850 - 700 hPa, 500 - 300 hPa and 200 - 100 hPa were presented diagrammatically in Figs. 10-12, representing lower, middle and upper troposphere. Table 4 (a) summaries the LRAs for normal rainfall years.

The LRAs for normal rainfall years are very small when compared with the LRAs of excess or deficient rainfall years. This is because of the fact that the contribution from normal rainfall years (*i.e.*, 20 normal rainfall years in 29 years of study) is more in normal values of lapse rates. Monthwise results of LRAs are discussed below:

3.3.1. *March*

In comparison with excess rainfall years Surface – 850 hPa the LRAs were positive (cooler air mass) over north India during March. This indicates that in lower



Figs. 10(a-d). Average lapse rate anomaly ($^{\circ}\text{C}/\text{km}$) 0000 & 1200 UTC for March (Normal rainfall years). Shaded portions indicate the negative values (a) Sur - 850 hPa, (b) 850 - 700 hPa, (c) 500 - 300 hPa and (d) 200 - 100 hPa

levels the atmosphere was warmer throughout the country for excessive rainfall years where as for normal years the peninsular India had the warmer air in the lower levels. But this is not seen in the layer 850 - 700 hPa.

For 500 - 300 hPa level the LRAs were positive for normal years while they were negative for excessive rainfall years.

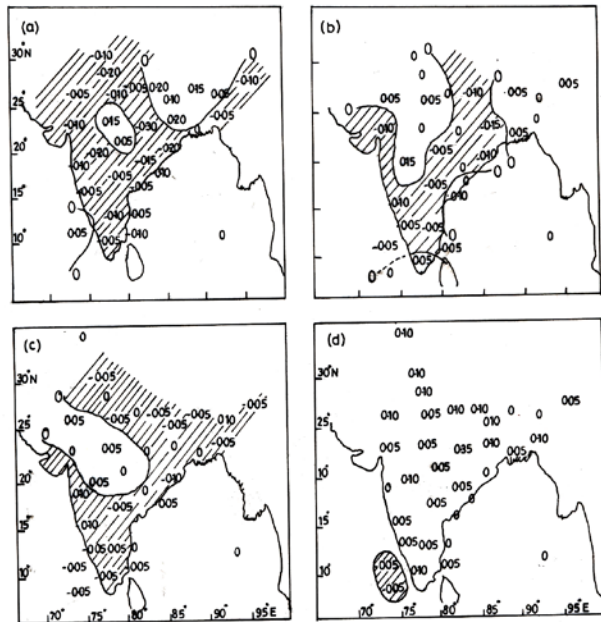
At 200 - 100 hPa LRAs were positive for excessive and deficient years where as they were mainly negative for the normal years.

3.3.2. *April*

In comparison with excess rainfall years the area with positive LRAs (cooler air mass) was more at 850-700 hPa. In normal rainfall years NE India had positive LRAs at 850 - 700 hPa while for excess rainfall years they were negative in that region.

At 500-300 hPa level LRAs were negative over most part of the country except western parts of central India and some parts of NW India, while they were negative over most part of the country for excess rainfall years.

At 200 - 100 hPa, LRAs were positive for normal rainfall years while they were negative for excess or deficient rainfall years.



Figs. 11(a-d). Average lapse rate anomaly ($^{\circ}\text{C}/\text{km}$) 0000 & 1200 UTC for April (Normal rainfall years). Shaded portions indicate the negative values (a) Sur - 850 hPa, (b) 850 - 700 hPa, (c) 500 - 300 hPa and (d) 200 - 100 hPa

3.3.3. May

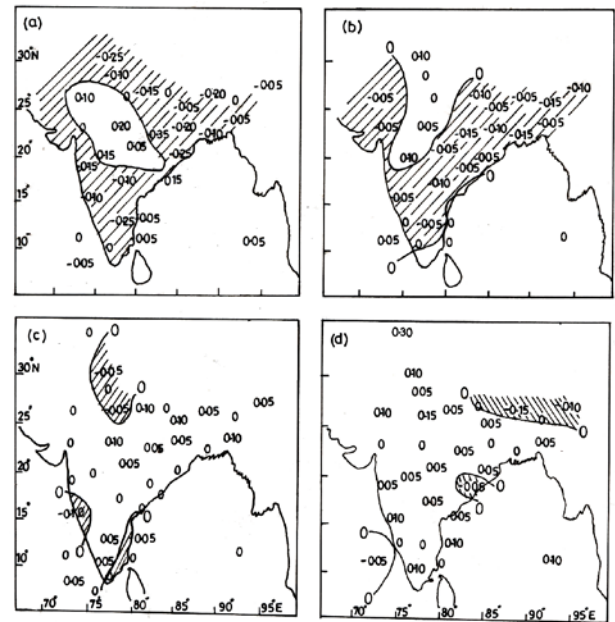
For normal rainfall years at Surface – 850 hPa, central parts of India and parts of NW India had positive LRAs where as rest of the country had negative LRAs. Most parts of the country were having positive LRAs for deficient rainfall years while LRAs were negative over most parts of the country for excess years.

At 850 - 700 hPa LRAs were negative over most parts of the country and similar was the case with excess rainfall years. However, the areas with positive LRAs were different. But in comparison with deficient rainfall years, the areas of positive and negative LRAs were exactly reverse.

At 500 - 300 hPa normal rainfall years were similar to deficient rainfall years where as at 200-100 hPa level it resembles excess rainfall years.

At 200 - 100 hPa LRAs were mainly positive throughout the country except for some negative areas at foot hills. This resembles the excess rainfall years while it is just opposite of deficient rainfall years.

From above observations we can definitely say that for normal and excess rainfall year lower layers are warmer and upper troposphere has cooler air. High values of negative LRAs are noticed for excess rainfall years in



Figs. 12(a-d). Average lapse rate anomaly ($^{\circ}\text{C}/\text{km}$) 0000 & 1200 UTC for May (Normal rainfall years). Shaded portions indicate the negative values (a) Sur - 850 hPa, (b) 850 - 700 hPa, (c) 500 - 300 hPa and (d) 200 - 100 hPa

comparison with normal rainfall years. For deficient rainfall years the lower troposphere levels are having cooler air mass and upper troposphere has warmer air mass.

3.4. Comparative study of LRAs during excessive and deficient monsoon years

To have a clear understanding about the distribution of LRAs during excessive/deficient monsoon years the above points were presented in a tabular form [Table 4 (b-c)] respectively giving importance to the area covered by the negative or positive anomalies.

From Table 4(b) it was seen that during excess monsoon rainfall years the actual lapse rates were less than normal lapse rate (*i.e.*, negative anomalies) in the month of March from surface to 300 hPa there by suggesting that the atmosphere was warmer from surface to 300 hPa and cooler above 300 hPa, *i.e.*, unstable atmosphere in the lower levels followed by a stable atmosphere in the higher levels which was congenial for convective activity.

In April the atmosphere was unstable in the lower and upper troposphere while it was stable in the middle troposphere. During May the atmosphere was unstable up to 200 hPa and followed by a stable layer from 200 to 100 hPa.

TABLE 4 (a)

Lapse rate anomalies for normal rainfall years

		March	April	May
Lower Troposphere	Surface– 850 hPa	Negative over peninsular and some parts of SE central India	Negative (part of central India, parts of Bihar and West Bengal eastern parts of NE India)	Negative anomaly (except central India and eastern parts of NW India)
	850 – 700 hPa	Negative all over the country except NW India and some parts of peninsular India	Negative anomalies (except NE India, western parts of central India, northern parts of NW India and northern parts of north India)	Negative except western parts of India, parts of northern India
Middle Troposphere	700 – 500 hPa	Positive all over the country	Positive except parts of central and northern India	Mainly positive except small pocket in peninsular India and parts of foot hills
	500 – 300 hPa	Positive all over the country except parts of Gujarat and some parts of northern India	Negative except western parts of central India and parts of NW India	Mainly positive except some parts of west and east and parts of foot hills
Upper Troposphere	300 – 200 hPa	Negative all over the country except some parts of north India	Negative over the country except eastern parts and central and northern India and west parts of NE India and some parts of SE peninsular India	Almost no deviation
	200 – 100 hPa	Negative over the country except northern parts of north India, some parts of central India and southern most parts of peninsular	Positive all over the country	Mainly positive except some parts of NE India

TABLE 4 (b)

Lapse rate anomalies for excessive rainfall years

		March	April	May
Lower Troposphere	Surface – 850 hPa	Negative over the country (except some peninsular parts)	Negative anomalies (except NW peninsular, Kutch and some parts of east coast and foothills)	Negative anomalies (except some parts of peninsular India)
	850-700 hPa	Negative over the country	Negative anomalies	Negative (except some parts of central and peninsular India)
Middle Troposphere	700-500 hPa	Negative over the country	Negative in peninsula (except west coast) Positive over northern India	Positive anomalies over the country (except north east India)
	500-300 hPa	Negative over the country	Mainly positive	Negative anomalies (except Kutch)
Upper Troposphere	300-200 hPa	Mainly positive anomalies	Anomalies are negative	Anomalies are negative (except a belt from 25° N to 30° N)
	200-100 hPa	Mainly positive anomalies	Anomalies are negative	Anomalies are positive

TABLE 4 (c)

Lapse rate anomalies for deficient rainfall years

		March	April	May
Lower Troposphere	Surface – 850 hPa	Positive anomalies (except north east India, NE parts of peninsular India and Kutch)	Positive anomalies (Eastern parts of Bihar, sub-Himalayan West Bengal, western parts of central India)	Positive (except Gujarat, parts of Maharashtra and Kerala)
	850-700 hPa	Positive Anomalies (except northern parts of northwest India)	Positive anomalies (except western parts of north west India and north east India)	Positive (except a small region (17° N to 30° N) and 75° E and 80° E)
Middle Troposphere	700-500 hPa	Negative anomalies (except southern parts of NW India)	Mainly negative anomalies over India	Negative over the country
	500-300 hPa	Negative anomalies (except NW India and northern parts of north India)	Positive anomalies (except southern parts of NW India, Gujarat and Kutch, western parts of central India)	Mainly positive
Upper Troposphere	300-200 hPa	Negative anomalies over North India, Positive anomalies over south India	Positive anomalies over the country	Mainly positive anomalies
	200-100 hPa	Positive anomalies over India (except for small pockets of negative anomalies)	Negative anomalies over the country	Negative over the country

TABLE 4 (d)

Comparison of lapse rate anomalies (March and April)

	Excess rainfall years	Normal rainfall years	Deficient rainfall years
Surface – 850 hPa	NW parts of peninsula and Gujarat region have positive anomalies. Rest of the country has mainly negative anomalies	Parts of central India, foot hills of Himalayas and parts of NE have positive anomalies. Rest of the country has negative anomalies. The anomaly values are comparatively smaller than that for excess rainfall years	Except foot hills of Himalayas and Gujarat region whole country has positive anomalies
850 – 700 hPa	Parts of NW India and central and north India have positive LRAs. Rest of India has negative anomalies	Are above 25° N and southern most parts of peninsula have positive anomaly. Rest of the country has negative anomalies. The values of anomalies are small as compared to that of excess rainfall year	Except NW India and parts of NE India whole country has positive anomalies
700 – 500 hPa	NE India, north India and western parts of central India have positive anomaly. Rest of the country except some parts of west coast have negative anomalies	Parts of central and northern India have negative anomalies where as rest of the country has positive anomaly. Comparatively warmer than excess and normal	Parts of NE India, NW India and central India have positive anomalies where as major parts of India is having negative anomaly
500 – 300 hPa	Western parts of central India, western parts of peninsular region and some parts of north India have positive anomaly, east coast and west coast stations also have positive anomaly, NW India, NE India and eastern parts of central and north India have negative anomalies	NW India, parts of north India and peninsular region have negative anomalies. The values are very small compared to excess rainfall years. Major parts of India have positive anomalies	NE India, central India and northern parts of peninsular India have negative anomalies. Comparatively cooler air mass in the major parts as India
300 – 200 hPa	Central India, parts of foot hills and southern peninsular India have negative anomaly	All most all parts of the country has negative anomalies	North of 23° N have mainly negative anomalies
200 – 100 hPa	Except some parts of peninsular India west of 80° E have negative anomalies	NE India, major parts of peninsular India have negative LRAs	Except southern parts of peninsular India mainly negative anomalies over the country

During deficient rainfall years [Table 4(c)] from March to May the atmosphere was stable from surface to 700 hPa followed by an unstable layer from 700 to 500 hPa. Beyond 500 hPa there were pockets of stable and unstable layers existing side by side over the country.

In a nut shell one can say that in the pre-monsoon months (March-May) if the atmosphere was unstable in the lower and middle troposphere followed by a stable layer in the upper troposphere, the ensuing monsoon season was likely to be an excess rainfall year. In the pre-monsoon months if the atmosphere was stable in the lower troposphere with an unstable layer in the middle/upper troposphere then the ensuing monsoon was likely to be a deficient rainfall year.

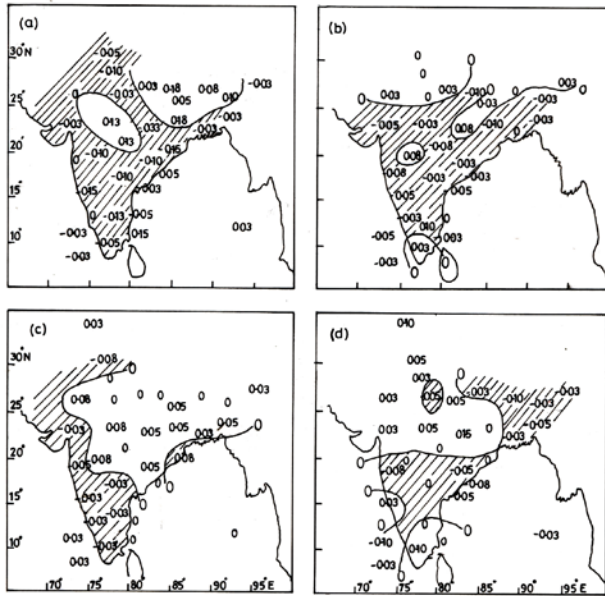
3.5. Comparative study of LRAs for combination of months (March & April)

In order to find out whether the combination of two or three months data give indication to the ensuing monsoon season rainfall we have studied combined

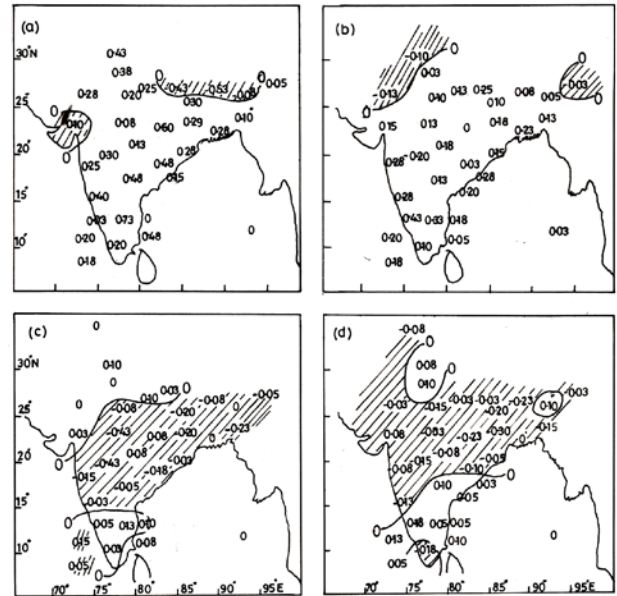
average lapse rate anomalies for March and April. We did not study the other combinations like March, April and May, March and May or April and May as sufficient time is not there for forecasting purposes taking June 1st as the normal date of onset. Comparison of the distribution of LRAs for (March and April) excess, normal and deficient rainfall years are presented in Table 4 (d). The analysed charts of LRAs for normal, excess and deficient years are presented in Figs. 13-15.

3.5.1. Surface – 850 hPa and 850 – 700 hPa

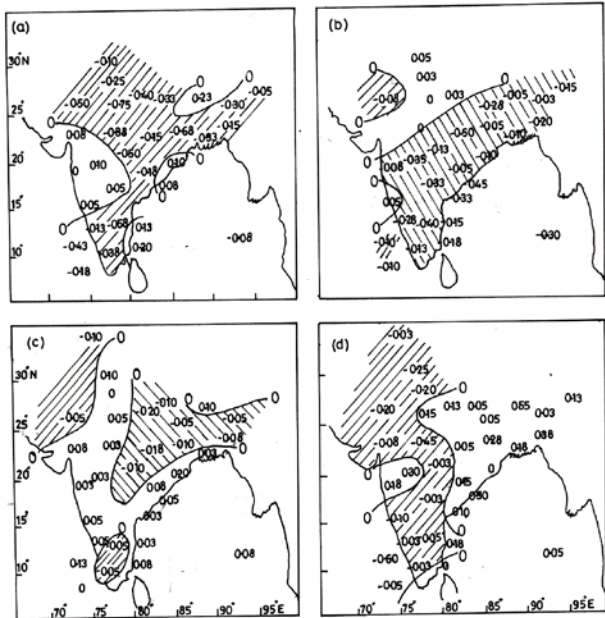
Though the area of distribution of positive and negative LRAs over India were different, there was resemblance in excess and normal rainfall years. However, the values of LRAs were comparatively smaller in normal monsoon years than excess rainfall years. The warmer air mass was present for normal and excess rainfall years but the air was still warmer in case of excess rainfall years (higher values of negative LRAs). For deficient rainfall years positive anomalies (cooler air) over Indian region were noticed.



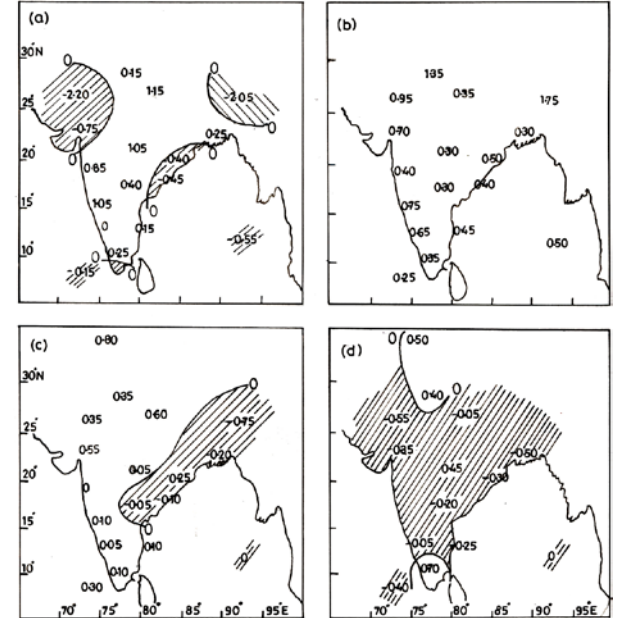
Figs. 13(a-d). Average lapse rate anomaly ($^{\circ}\text{C}/\text{km}$) 0000 & 1200 UTC for March + April (Normal rainfall years). Shaded portions indicate the negative values (a) Sur - 850 hPa, (b) 850 - 700 hPa, (c) 500 - 300 hPa and (d) 200 - 100 hPa



Figs. 15(a-d). Average lapse rate anomaly ($^{\circ}\text{C}/\text{km}$) 0000 & 1200 UTC for March + April (deficient rainfall years). Shaded portions indicate the negative values (a) Sur - 850 hPa, (b) 850 - 700 hPa, (c) 500 - 300 hPa and (d) 200 - 100 hPa



Figs. 14(a-d). Average lapse rate anomaly ($^{\circ}\text{C}/\text{km}$) 0000 & 1200 UTC for March + April (excess rainfall years). Shaded portions indicate the negative values (a) Sur - 850 hPa, (b) 850 - 700 hPa, (c) 500 - 300 hPa and (d) 200 - 100 hPa



Figs. 16(a-d). Average lapse rate anomaly ($^{\circ}\text{C}/\text{km}$) 0000 & 1200 UTC for March (year 2002). Shaded portions indicate the negative values (a) Sur - 850 hPa, (b) 850 - 700 hPa, (c) 500 - 300 hPa and (d) 200 - 100 hPa

3.5.2. 500-300 hPa

For normal rainfall years central India and north east India had positive anomalies and rest of the area had

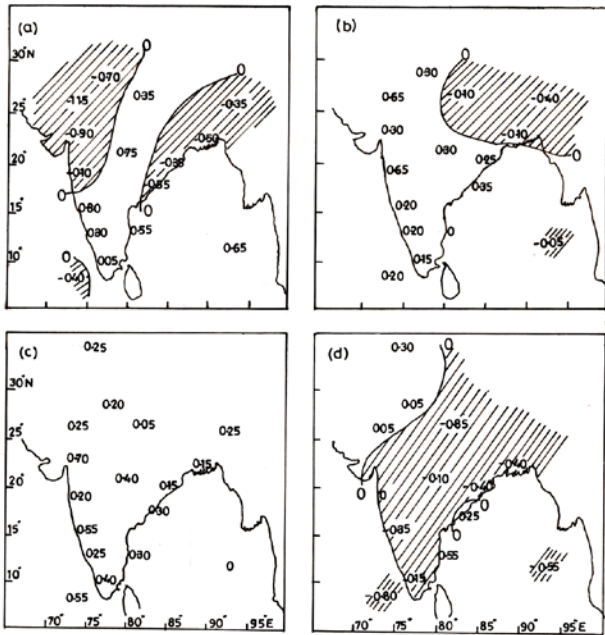
negative anomaly but for deficient as well as for excess rainfall years the areas of positive and negative anomalies were almost opposite. This means that normally at this layer air was comparatively cooler over central and

TABLE 5
Lapse rate anomaly values (Year 2002)

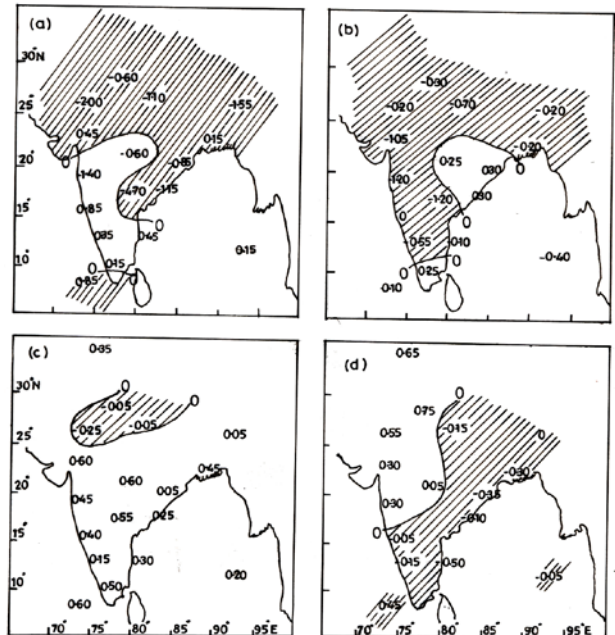
Station	Lapse rates anomaly (0000 + 1200) UTC																	
	March						April						May					
	Sur-850	850-700	700-500	500-300	300-200	200-100	Sur-850	850-700	700-500	500-300	300-200	200-100	Sur-850	850-700	700-500	500-300	300-200	200-100
Ahmedabad	-0.75	0.70	0.30	0.55	0.15	-0.35	-0.90	0.30	0.15	0.70	0.15	-0.45	-1.05	0.45	0.60	0.55	0.30	
Bhubaneswar	-0.40	0.50	0.05	-0.25	0.80	-0.30	-0.35	0.25	0.45	0.15	-0.30	-0.40	-0.85	0.30	0.35	0.05	0.25	-0.15
Cochin	0.25	0.35	0.10	0.10	0.45	0.70	0.05	0.15	0.20	0.40	0.85	-0.15	0.15	0.25	0.10	0.50	0.85	
Goa/Panjim	1.05	0.75	0.15	0.10	-0.25		0.80	0.20	0.30	0.55	0.40	-0.35	0.85	0.00	0.15	0.40	0.85	-0.05
Guwahati	-2.05	1.75	0.15	-0.75	1.35		-0.35	-0.40	0.15	0.25	-0.25		1.55	-0.20	0.55	0.05	-0.10	0.00
Hyderabad	0.40	0.65	-0.15	-0.05	0.75	-0.20							-4.70	-1.20	0.30	0.55	0.05	
Jodhpur	-2.20	0.95	0.15	0.35	-0.15	-0.55	-1.15	0.65	0.30	0.25	0.20	0.05	-2.00	-0.20	0.65	-0.25	0.80	0.55
Kolkata	0.25	0.30	0.15	-0.20	0.20	-0.50	-0.50	-0.10	0.50	0.15	-0.65	-0.40	-0.15	-0.20	0.30	0.45	-0.35	-0.30
Lucknow	1.15	0.35	0.50	0.50	-0.70	-0.05	0.35	-0.10	0.35	0.05	-0.35	-0.85	-1.10	-0.70	0.05	-0.05	0.40	-0.15
Madras	0.15	0.45	0.00	0.10	0.35	-0.25	0.55	0.00	0.20	0.30	0.20	-0.55	0.45	-0.10	0.25	0.30	0.20	-0.50
Mangalore	0.00	0.65	-0.30	0.05	0.55	-0.05	0.30	0.20	-0.10	0.25	0.55		0.35	-0.55	-0.05	0.15	0.10	-0.15
Minicoy	-0.15	0.25	0.15	0.30	0.75	-0.40	-0.40	0.20	0.10	0.55	0.80	-0.80	-0.85	0.10	0.20	0.60	0.50	-0.45
Mumbai	0.85	0.40	-0.05	0.00	0.30		-0.10	0.65	-0.15	0.20	0.00	0.00	1.40	-1.20	-0.15	0.45	0.25	0.30
Nagpur	1.05	0.30	-0.05	0.05	0.75	-0.45	0.75	0.30	0.25	0.40	-0.25	-0.10	0.60	0.25	-0.35	0.60	0.00	0.05
New Delhi	0.15	1.35	0.75	0.35	0.50	0.40	-0.70	0.30	0.40	0.20	0.15	0.05	-0.60	-0.30	0.20	-0.05	0.45	0.75
Port Blair	0.55	0.50	0.00	0.00	0.15	0.00	0.65	-0.05	0.35	0.00	0.35	-0.55	0.15	0.40	0.15	0.20	0.25	0.05
Srinagar			-0.90	0.80	-0.55	0.50			0.05	0.25	-0.80	0.30			0.80	0.35	-0.65	0.65
Thiruvananthapuram	-0.35	0.35	0.30	0.20	0.70	0.05	0.20	0.10	0.15	0.15	0.40	0.00	-3.05	2.65	0.25	0.25	0.75	-0.45
Visakhapatnam	-0.45	0.40	0.10	-0.10	0.30		-0.55	0.35	0.25	0.30	0.00	0.25	-1.15	0.30	0.50	0.25	-0.10	-0.10

TABLE 6
Lapse rate anomalies for the year 2002

	March		April		May	
Lower Troposphere	Surface – 850 hPa	Positive anomalies (except some parts of peninsular India and NW India) over the country	Positive anomalies (except NE India and NW India) over the country		Predominantly negative anomalies over the country (Except parts of peninsula and central India)	
	850-700 hPa	Positive anomalies over the country	Positive anomalies over the country except NE India		Predominantly negative anomalies over the country (Except extreme south peninsula, Orissa and Chattisgarh)	
Middle Troposphere	700-500 hPa	Mainly positive anomalies over the country	Positive anomalies over the country		Positive anomalies over the country	
	500-300 hPa	Positive anomalies (Except NE India and NE parts of peninsular India)	Positive anomalies over the country		Positive anomalies over the country	
Upper Troposphere	300-200 hPa	Mainly positive anomalies	Positive anomalies over the country		Positive anomalies over the country	
	200-100 hPa	Negative over India (except small areas of north India and southern most parts of peninsular India)	Negative anomalies over India (Except NW India)		Positive and negative anomalies existing side by side with negative anomalies occupying a larger area	



Figs. 17(a-d). Average lapse rate anomaly ($^{\circ}\text{C}/\text{km}$) 0000 & 1200 UTC for April (year 2002). Shaded portions indicate the negative values (a) Sur - 850 hPa, (b) 850 - 700 hPa, (c) 500 - 300 hPa and (d) 200 - 100 hPa



Figs. 18(a-d). Average lapse rate anomaly ($^{\circ}\text{C}/\text{km}$) 0000 & 1200 UTC for May (year 2002). Shaded portions indicate the negative values (a) Sur - 850 hPa, (b) 850 - 700 hPa, (c) 500 - 300 hPa and (d) 200 - 100 hPa

northeast India. It is noticed that the values of LRAs were very small for normal years.

3.5.3. 200-100 hPa

For normal rainfall years northern parts of India and southern peninsular India had positive LRAs and rest of the country had negative LRAs. For excess rainfall years eastern parts of central India and north east India had positive LRAs, whereas for deficient rainfall years mainly peninsular India had positive LRAs.

4. Lapse rate anomalies during 2002

The study was extended further to see the LRA distribution during summer season of 2002 as June to September of 2002, was one of the worst deficient rainfall years (monsoon rainfall -19% of LPA). We examined the upper-air characteristics using the available CLIMAT TEMP data. The data were available for 19 stations only. The anomaly values were presented in Table 5. The LRA charts were analysed from March to May for all six layers. However, the charts for surface to 850 hPa, 850 - 700 hPa, 500 - 300 hPa and 200 - 100 hPa were presented in Figs. 16-18.

In the month of March the LRAs were predominantly positive over the country from surface to

800 hPa [Figs. 16 (a-c)]. The LRAs were predominantly negative between 200-100 hPa [Fig. 16(d)].

In the month of April, in the surface – 850 hPa layer [Fig. 17 (a)] the LRA were negative over north and north west India, Gujarat, parts of Maharashtra, north coastal Andhra Pradesh, Orissa, West Bengal, adjoining parts of Bihar and NE India. From 850 - 200 hPa the LRAs were predominantly positive [Fig. 17 (b-c)]. Between 200-100 hPa the LRAs were negative over the country except over NW India and parts of north India [Fig. 17(d)].

In the month of May 2002, the LRAs were predominantly negative from surface to 700 hPa [Figs. 18 (a&b)]. The LRAs were positive over the country except for small pockets of negative LRAs between 700 - 200 hPa [Fig. 18(c)]. The positive and negative LRAs were existing side by side between 200 - 100 hPa [Fig. 18(d)] with negative anomalies occupying a larger area.

These above results were presented in a tabular form (Table 6). In May 2002 even though the atmosphere was unstable to some extent between surface - 700 hPa, the convective activity was inhibited as stable atmospheric layer was present from 700 to 200 hPa. This pattern was similar to the characteristics of deficient monsoon rainfall years studied in the earlier section.

Thus the LRAs from March to May of 2002 give a clear indication of deficient monsoon rainfall from June to September, 2002.

Similar study of LRAs of summer season for the year 2004 (monsoon rainfall –13% of LPA) was done using CLIMAT TEMP data and data for 17 stations were available. The analysis revealed that the LRAs during March and April over Indian region show close resemblance with the mean LRAs of deficient rainfall year at all layers. This case study also shows that LRAs of summer season will give clear indication of the ensuing monsoon rainfall.

5. Conclusions

From the above discussions it can be concluded that

(i) If the LRAs during March to May were negative and present an unstable layer in the lower and middle troposphere followed by a positive LRAs (a stable layer) in the upper troposphere then the ensuing monsoon rainfall was likely to be excess.

(ii) If the LRAs during March to May were positive and present a stable layer in the lower and middle troposphere followed by negative LRAs (an unstable layer) in the upper troposphere then the ensuing monsoon rainfall was likely to be deficient.

(iii) For the years 2002 and 2004, the LRAs distribution was similar to that of the deficient years.

(iv) The mean lapse rate values presented in the Table 1 can be used for working out the anomaly values for the individual years.

(v) Lapse rate anomaly (LRA) distribution over the country during March – May thus give a clear indication about the ensuing all India summer monsoon rainfall

qualitatively. LRF unit of the department can use this parameter as one of the predictors for qualitative assessment of the ensuing summer monsoon rainfall as the statistical models generally fail in extreme cases.

(vi) Normal rainfall monsoon years and excess rainfall monsoon years have similar features but the LRAs are of higher values for excess rainfall years *i.e.*, lower levels are warmer and upper troposphere is cooler for both excess and normal rainfall years. But for excess rainfall years it is warmer than normal rainfall years at lower levels.

(vii) Combination of March and April months LRAs also show similar results.

Acknowledgements

The authors acknowledge the sincere efforts of Mrs. Sheeja Kurian in keying in the manuscript and the preparation of Tables.

References

- Ananthkrishnan, R. and Soman, M. K., 1989, "Further examination of the anomaly in the radiosonde data of Ahmedabad", *Mausam* **40**, 3, 283-286.
- Frederiksen, C. S. and Frederiksen, J. S., 1992, "Northern hemisphere cyclonic storm tracks and teleconnection patterns in primitive equation and quasigeostrophic models", *J. Atmos. Sci.*, **49**, 1443-1458.
- Gates, W. L., 1961, "Static stability measures in the atmosphere", *J. Meteor.*, **18**, 526-533.
- Lee, W. J. and Mak, M., 1994, "Observed variability in the large scale static stability", *J. Atmos. Sci.*, **51**, 2137- 2144.
- Mak, M., 1993, "Local baroclinic instability induced by inhomogeneous static stability", *J. Atmos. Sci.*, **50**, 1629-1642.
- Rajeevan, M., 1991, "Upper-air circulation and thermal anomalies over India and neighborhood *vis-à-vis* Indian summer monsoon activity", *Mausam*, **42**, 2, 155-160.