MAUSAM, 50, 1 (January 1999), 1-8

551.577.22(547.1)

A diagnostic study of contrasting rainfall epochs over Mumbai

S.N. DUTTA and U.S. DE

Meteorological Office, Pune - 411005, India

(Received 10 June 1997, 23 February 1998)

सार — मुम्बई में मानसून ऋतु के दौरान विषम वर्षा स्थितियों (क्रमागत दिनों में) से सम्बद्ध सिनाप्टिक फीचर और कुछ गतिक एवं उष्मागतिक प्राचलों की जाँच करने का प्रयास किया गया है। इसमें दो विषम मानसून वर्षों यथा 1987 (खराब मानसून वर्ष) और 1988 (अच्छा मानसून वर्ष) का अध्ययन किया गया है। इस अध्ययन में मुम्बई के रेडियो सौन्दें आंकड़ों का उपयोग किया गया है।

बहुत सी स्थितियों में मुम्बई में विलगित दिन में निम्नलिखित सिनॉप्टिक सिस्टमों से सम्बद्ध भारी वर्षा पाई गई है (क) समुद्र सतह चार्ट के अनुसार महाराष्ट्र के तट के पार पश्चिमी तट के सहारे द्रोणी में और (ख) निम्न/मध्य क्षोभमंडलीय स्तर में गुजरात में एक चक्रवातीय परिसंचरण (साइसर)।

उपर्युक्त दो सिस्टमों में से कम से कम एक सिस्टम हल्की वर्षा के दिनों में समाप्त हो जाता है।

आर्द्र स्थैतिक ऊर्जा के भारित औसत मान भारी वर्षा वाले दिन अधिक होते हैं। अधिकांश स्थितियों में भारी वर्षा वाले दिन संवहनी उपलब्ध विभव ऊर्जा (केप) भी अधिक होते हैं। अधिकांश स्थितियों में, भारी वर्षा वाले दिनों में एल एफ सी कम होती पाई गई है। विषम दिनों में वर्षा की परिवर्तनशीलता के बारे में उपरितन वायु प्रवाह प्रतिरूप और स्कोरर प्राचलों के विचलन के बहुत रोचक संकेतों का पता चलता है।

ABSTRACT. An attempt has made to diagnose the synoptic features and some dynamic and thermodynamic parameters associated with contrasting rainfall situations (on consecutive days) during the monsoon season, over Mumbai. Study has been made for two contrasting monsoon years, *viz*, 1987 (Bad monsoon year) and 1988 (Good monsoon year). For this study RS data of Mumbai have been used.

In many cases heavy rainfall on an isolated day over Mumbai is associated with the following synoptic systems - (a) a trough on sea level chart running along west coast through Maharashtra Coast and (b) a cyclonic circulation (CYCIR) over Gujarat in the lower/middle tropospheric level.

At least one of the above two systems ceased to exist on the days of light rainfall.

Weighted average value of moist static energy is more on the day of heavy rainfall. In most of the cases convective available potential energy (CAPE) is also more on the day of heavy rainfall. LFC, on most of the cases, is seen to have lowered down on the days of heavy rainfall. Variation in upper air flow pattern and scorer parameter also gave very interesting clues to variation of rainfall on contrasting days.

Key words — Monsoon rainfall, Thermodynamic parameters, Convective available potential energy, LFC, Synoptic features, Scorer parameter.

1. Introduction

It is often observed that Mumbai gets contrasting amount of rainfall on two consecutive days during the summer monsoon season. On some of the occasions this contrasting rainfall is associated with near similar synoptic situations on two consecutive days and on some another occasion it is associated with different synoptic situations. Similar type of studies for different tropical regions were carried out by Riehl (1954), Reihl *et al.* (1973). Their studies were regarding precipitation over tropical oceanic and land regions, mostly confined to Carribean and the Pacific regions of the tropics. They had shown that days associated with less or no precipitation activity did not contain less moisture than the days with good rainfall.

Anantkrishnan *et al.* (1965) had also shown that precipitable water contents (PWC) varies from 5.2 to 6.2gm/cm^2 during the summer monsoon months over Mumbai. They had also shown that although rainfall over Mumbai decreases nearly by a factor 2 from July to August, the decrease in moisture content is extremely small. Srinivasan and Sadasivan (1975) have shown that above 850 hPa the air is generally partially saturated during weak monsoon condition.

Sarker *et al.* (1978) obtained a better approximation of rainfall from their modified orographic rainfall model on incorporation of the above findings of Srinivasan and Sadasivan. Mukherjee and Ramana Murthy (1978) studied contrasting rainfall features and associated thermodynamic behaviour over Mumbai. They computed PWC, stability and convective instability. They found that higher rainfall days are associated with higher static stability, less convective instability and higher PWC. They also found that difference in static stability and PWC between consecutive days of contrasting rainfall were not significant.

In this paper studies similar to Mukherjee and Ramana Murty (1978) have been carried out except but additional dynamical and thermodynamical parameter have considered.

In this study we have computed the moist static energy (MSE) which is a measure of moist static stability, convective available potential energy (CAPE), precipitable water content (PWC), scorer parameter (SP), zonal wind variation with height (du/dz) and lower most level moist instability index. Also we have examined synoptic situations associated with contrasting rainfall days.

2. Data

Contrasting rainfall days have been selected from daily rainfall data of Mumbai during monsoon season for 1987 and 1988 obtained from National Data Centre (NDC), ADGM(R) office, Pune and RS data of Mumbai have also been collected from NDC, ADGM(R) office, Pune.

3. Methodology

MSE have computed using the following formula :

$$MSE = CpT + gZ + Lqs \tag{1}$$

Where,

Cp = Specific heat at constant pressure

T = Temperature in absolute scale

g = Acceleration due to gravity

Z = Height of the pressure level

L = Latent heat of evaporation

qs = Saturated specific humidity

After computing MSE at each level, weighted average of it have also been computed using the formula

$$\text{weighted average of MSE} = \frac{\sum_i \text{MSE}(i)\, Z(i)}{\sum Z(i)} \tag{2}$$

where the summation is extended from 1000 to 400 hPa, since on the days under study moisture was not available beyond 400 hPa, over Mumbai.

Convective available potential energy (CAPE) has been computed using the following formula :

$$CAPE = \int_{z_{LFC}}^{z_{LNB}} \frac{g\,(T_{\text{Parcel}} - T_{\text{Env}})}{T_{\text{Env}}}\, dz \tag{3}$$

$$= \int_{P_{LFC}}^{P_{LNB}} -R\,(T_{\text{Parcel}} - T_{\text{Env}})\, d\,(\text{LNP}) \tag{4}$$

where, LFC is level of free convection and LNB is level of neutral buoyancy. (Since in maximum cases LNB was not found, hence the above two integrals are extended from LFC to 200 hPa).

CAPE has been computed using equations (3) and (4). The integrals in equations (3) and (4) have been numerically calculated using trapezoidal rule. Scorer parameter (SP) have been computed using the following equations :

$$SP = \frac{\frac{g}{\theta}\frac{\partial\theta}{\partial Z}}{U^2} - \frac{1}{U}\frac{d^2U}{dZ^2} \tag{5}$$

The differential approximation in equation (5) has been numerically computed using central difference formula except for the boundary levels, where it has been computed using forward and backward difference formula.

Precipitable water content (PWC) in gm/cm^2 have been calculated using the following formula :

$$PWC = -\frac{1}{g}\int r\,dp \tag{6}$$

where,

r = mixing ratio in gm/kg

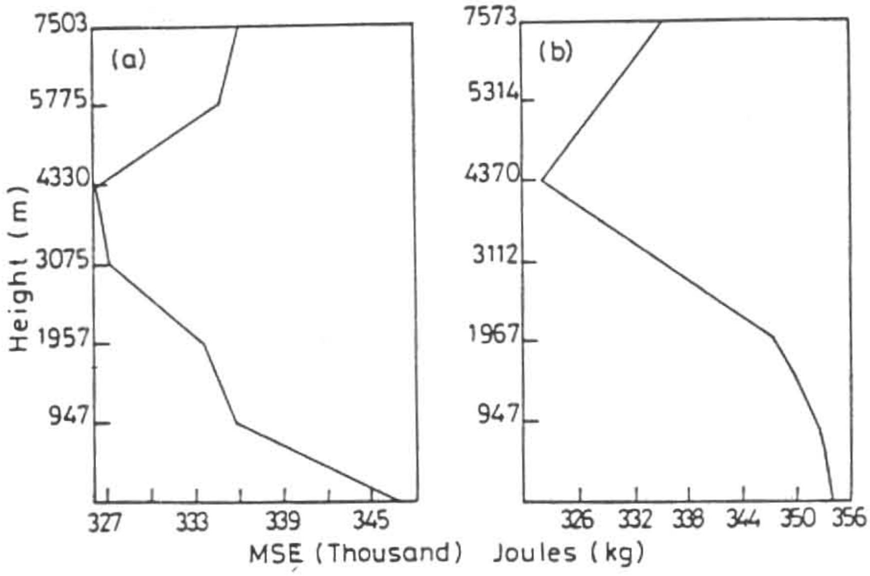
The above integral is extended from 1000 to 500 hPa and it has been numerically calculated using trapezoidal rule. Murakami (1977) used an index (*Ie*), called index for moist stability in the lower most layer for studying instability in the lower troposphere. The expression of *Ie* is given by

$$Ie = \frac{\theta_{e_{850}} - \theta_{e_s}}{P_s - 850} \times 100 \tag{7}$$

where $e\theta_{e850}$ = Equivalent potential temperature at 850 hPa

θ_{e_s} = Equivalent potential temperature at surface

P_s = Surface pressure



Figs.1(a & b). Vertical profiles of moist static energy

Here, we have used a slightly modified form of *Ie*, which is given by,

$$Iem = \frac{\theta_{e_{900}} - \theta_{e_{1000}}}{1000 - 900} \times 100 \qquad (8)$$

$\theta_{e_{900}}$ being equivalent potential temperature at 900 hPa

and

$\theta_{e_{1000}}$ being equivalent potential temperature at 1000 hPa.

4. Discussion

4.1. *Synoptic features*

Case I—15 and 16 June 1987

On 15 June Mumbai received 12 cm rainfall where as on 16 June Mumbai receive 4 cm rainfall.

There was a trough extending from north Kerala Coast to south Gujarat Coast on the sea level chart and a cyclonic circulation (CYCIR) over east central Arabian Sea off Maharashtra Coast between 5.8 km and 7.6 km asl on 14 June and they were persisted on 15th also. But on 16th the CYCIR became unimportant and the trough was running from north Kerala Coast to south Maharashtra Coast.

Case II—7 and 8 July 1987

Mumbai received 13 cm and 1.3 cm rainfall on these two consecutive dates.

On 6th *i.e.*, one day before the spell there was a trough on sea level chart over east Arabian Sea extending from south Gujarat to north Kerala Coast, persisted on 7th but became less marked on 8th.

Case III — The periods between 16 to 18 August 1987 and 19 to 21 August 1987

The average amount of rainfall received by Mumbai during the period 16 to 18 August 1987 was 2.1 cm and that during the period 19 to 21 August 1987 was 10.6 cm. A cycir over Gujarat and neighbourhood in the lower troposphere extend on 18th. Further during 19th to 21st August 1997 there was a trough over east central Arabian Sea off Maharashtra Coast and a eastwest trough at 700 hPa running roughly along 20°N across the country. Also on the last day of this period there was a CYCIR lying over NE Arabian Sea and Adjoining land areas in lower tropospheric levels. There was no other synoptic system.

Case IV—17 and 18 June 1988

In this case synoptic situations were not much different between the days of contrasting rainfall. On both the days there was a trough on sea level chart from Gujarat to Lakshadweep area and a CYCIR over south Gujarat in the lower middle troposphere, although the days received contrasting amount of rainfall, *viz.*, 1.5 cm on 17th and 10 cm on 18th.

Case V—23 - 24 July and 25 - 26 July 1988

The average amount of rainfall at Mumbai during the former period was 10.3 cm, whereas during the later period it was 1.3 cm.

TABLE 1

Weighted average value of MSE, Static Stability, Convective Instability and Moist Instability in the lowermost layer

Case	Dates	Rainfall (cms)	MSE (J/kg)	Static Stability $*10^4(^{\circ}k\ mb^{-1})$	Convective Instability $*10^4(^{\circ}k\ mb^{-1})$	Moist Instability in the layer between 1000 & 900hPa
i	15 Jun'87	12.0	340756	0.1152	0.0012	-0.926
	16 Jun'87	04.0	342677	0.1121	0.0010	3.696
ii	7 Jul'87	12.0	333548	0.0978	-0.0166	-0.923
	8 Jul'87	01.3	332842	0.0930	-0.0362	-4.615
iii	18 Jun'88	09.8	331793	0.0946	-0.0345	-7.400
	17 Jun'88	01.5	332103	0.0955	-0.0411	-18.440
iv	19-21 Aug'87	11.0 (Average)	336551	0.1011	-0.0138	-2.210
	16-18 Aug'87	02.0 (Average)	336009	0.1285	0.0232	1.190
v	23-24 Jul'88	10.3 (Average)	339677	0.1149	0.0031	-4.570
	25-26 Jul'88	01.4 (Average)	342675	0.1210	0.0047	0.740
vi	28-29 Sep'88	13.1 (Average)	341019	0.1201	0.0233	6.419
	26-27 Sep'88	01.9 (Average)	337676	0.0995	-0.0192	-8.004

TABLE 2

Convective Available Potential Energy (CAPE), Precipitable Water Content (PWC), LCL level and LFC level for different cases

Case	Date	Rainfall (cms)	CAPE (A) (J/kg)	CAPE (B) (J/kg)	Precipitable water content (PWC) in gm/cm^2	LCL level (hPa)	LFC level (hPa)
i	15 Jun'87	12.0	0571.30	0586.00	5.30	985	820
	16 Jun'87	04.0	1043.45	1086.40	5.70	990	760
ii	17 Jul'87	12.0	1629.50	1675.55	4.53	985	880
	18 Jul'87	01.3	1503.93	1396.80	5.48	970	840
iii	19-21 Aug'87	11.0	1680.79	1214.11	5.29	975	850
	16-18 Aug'87	02.0	1722.27	1696.98	3.73	980	760
iv	16 Jun'88	09.8	2214.00	2425.39	4.42	970	870
	17 Jun'88	01.5	2144.00	1466.40	4.59	970	960
v	23-24 Jul'88	10.3	0941.02	0613.75	4.94	990	940
	25-26 Jul'88	01.4	0486.85	0452.50	5.54	970	840
vi	28-29 Sep'88	13.1	0216.20	0374.65	5.58	990	680
	26-27 Sep'88	01.9	0198.13	0278.51	5.11	980	940

During the period between 23 and 24 July 1988, on only one day there was trough extending from Maharashtra coast to Kerala coast on sea level chart.

This trough persisted on 25th also, but became less marked on 26th.

Case VI — The period between 26 & 27 September & 28 to 29 September 1988

Period from 26 to 27 September, 1988 when average rainfall was 1.9 cm and period from 28 to 29 September when average rainfall was 13.1 cm.

On 25, 26 & 27 September there was a trough on sea level chart extending from north Maharashtra Coast to Kerala Coast. On 27th there was a CYCIR between 1.5 km and 7.6 km above sea level off north Maharashtra Coast.

On 28th the trough on the sea level chart lay off south Maharashtra Coast, and the CYCIR off north Maharashtra Coast extended upto 5.0 km above sea level. On 29th the trough on sea level chart persisted at the same place and the CYCIR lay over north Konkan and adjoining Gujarat region and sea areas between 2.1 km and 4.5 km above sea level.

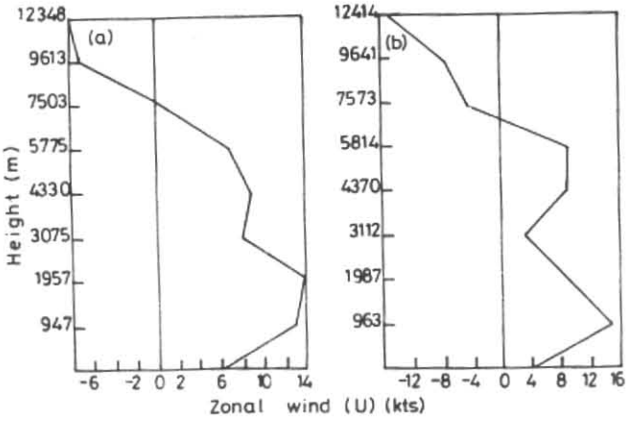
The graphical distribution of various dynamical, thermodynamical parameters are discussed in detail in the following section. However for brevity of space, the diagram in respect of one typical case has been given.

4.2. Moist static energy (MSE)

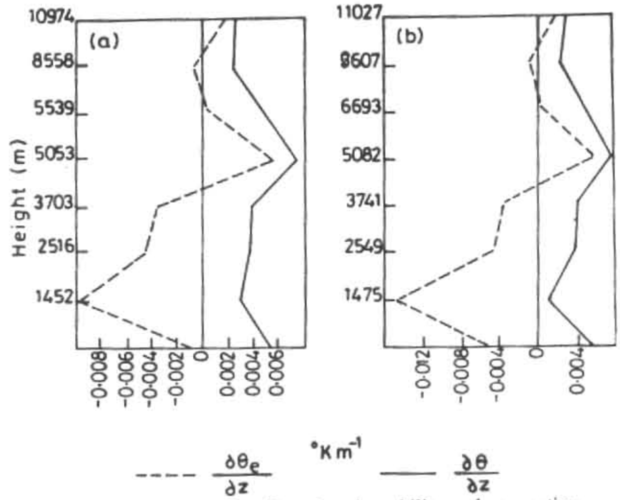
Vertical profiles of MSE upto 400 hPa are given in Figs. 1 (a -b) for a typical case (1) — 7th and 8th July 1987.

Case I — 7 and 8 July 1987

From the figure it can be seen that MSE decreased with height on both the days, then after obtaining a minimum value at a level in the middle troposphere, it started increasing with height. Here MSE attained the minimum value at a higher level on the day of light rainfall than that on the day of heavy rainfall. Also it can be seen from Table 1 that weighted average value of MSE on the day of heavy rainfall was about 700 Jkg^{-1} more than on the day of light rainfall.



Figs.2(a & b). Vertical profiles of zonal component of wind



Figs.3(a &b). Vertical profiles of static stability and convective instability

CaseII—15 and 16 June 1987

As in a previous case, it is seen that on both the days MSE first decreased with height, obtained a minimum value at a level in a mid-tropospheric layer and then increased with height. But it is clear from the figures that MSE attained minimum value at a higher level on the day of light rainfall than on the day of heavy rainfall. Also the weighted average value of MSE, as seen from Table 1, was more by 2000 Jkg^{-1} on the day of light rainfall.

Case III—17 and 18 June 1988

In this case, it is seen that MSE attained a minimum value at about 3.1 km asl and then it increased with height on both the day of light rainfall and heavy rainfall (17 June 1988 and 18 June 1988). In this case the vertical profile of MSE attained the minimum value almost at the same height asl. But weighted average value of MSE is more on the day of heavy spell.

Case IV—16-18 August and 19-21 August

During the former period of light rainfall the MSE initially remained almost stationary upto 1.9 km above sea level, then it started falling and attained the minimum value at 4.3 km above sea level. It remained with this minimum value upto 5.8 km and then it started increasing with height.

The minimum most value have attained at about 3.1 km asl and the another minimum value attained at about 5.8 km asl.

In this case also it is clear that minimum most value have been attained at a higher level during the period of light rainfall than during the period of heavy rainfall.

Here weighted average value of MSE is more during heavy rainfall period than on light rainfall period.

Case V—23 to 24 July and 25 to 26 July 1988

For this situations also the behaviour of the MSE and weighted average value of MSE are same. Here during former periods MSE attains two minimum, one at about 0.9 km above sea level another at about 3.1 km above sea level. But MSE have attained the minimum most value at 3.1 km above sea level.

For the later period MSE decreased with height first, then attaining minimum value at 3.1 km above sea level it starts increasing with height.

But in this case weighted average value of MSE is more on the day of light rainfall.

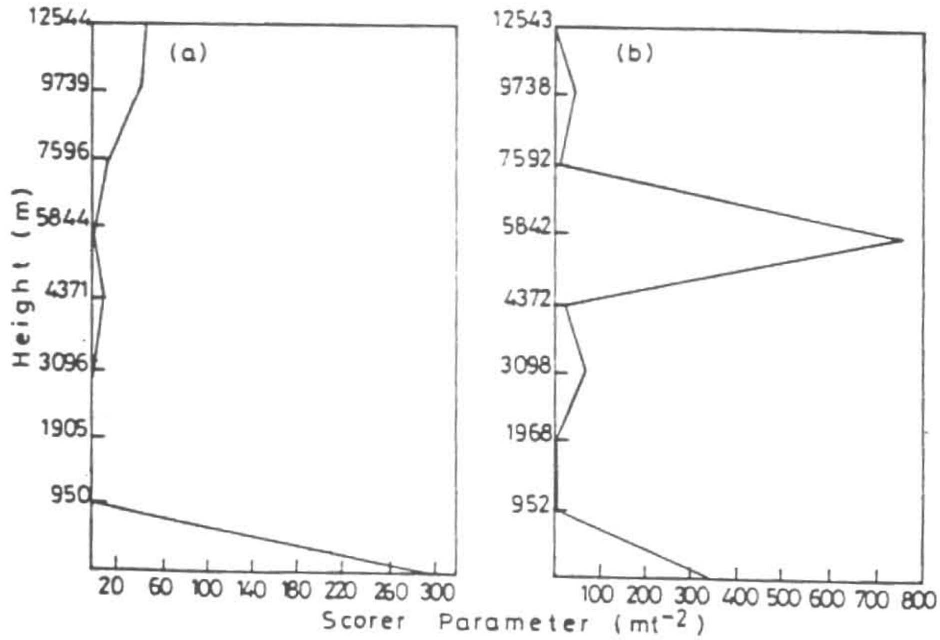
Case VI—28 to 29 September 1988 for heavy rainfall and 26 to 27 September 1988 for light rainfall

For this situation the days of heavy rainfall (28th and 29th September, 1988) MSE attains four minimum and three maximum, with maximum most value at about 1 km above sea level and minimum most value at about 3.1 km asl. But for the period of light rainfall (26th and 27th September, 1988) as in the earlier cases, MSE decreased with height, from a high value at 1000 mb, attained a minimum at about 3.1 km above sea level and then it increased with height. But weighted average value of MSE is more on the day of heavy rainfall.

4.3. Convective available potential energy (CAPE)

The values of CAPE for each case is given in Table 2. CAPE (A) is the values of CAPE as obtained using equation (3) and CAPE (B) is that using equation (4).

From the table we can see that out of six cases under study, in four cases CAPE on the day of heavy rainfall exceeds that on the day of light rainfall and in two cases we see just reverse.



Figs.4(a & b). Vertical profiles of scorer parameter

TABLE 3

Scorer parameter at different layers of atmosphere

Cases	Dates	Rainfall (cms)	1000 mb-900 mb	900 mb-800 mb	800 mb-700 mb	700 mb-600 mb	600 mb-500 mb	500 mb-400 mb	400 mb-300 mb	300 mb-200 mb
i	7 Jul'87	12.0	$0.13^{*}10^{-4}$	$0.33^{*}10^{-5}$	$0.54^{*}10^{-5}$	$0.87^{*}10^{-5}$	$0.13^{*}10^{-4}$	$0.24^{*}10^{-3}$	$0.23^{*}10^{-3}$	$0.62^{*}10^{-5}$
	8 Jul'87	01.3	$0.27^{*}10^{-4}$	$0.32^{*}10^{-5}$	$0.26^{*}10^{-4}$	$0.29^{*}10^{-4}$	$0.10^{*}10^{-4}$	$0.15^{*}10^{-4}$	$0.12^{*}10^{-4}$	$0.35^{*}10^{-5}$
ii	15 Jun'87	04.0	$0.18^{*}10^{-2}$	$0.25^{*}10^{-4}$	$0.34^{*}10^{-3}$	$0.41^{*}10^{-3}$	$0.40^{*}10^{-2}$	$0.39^{*}10^{-2}$	$0.24^{*}10^{-3}$	$0.21^{*}10^{-3}$
	16 Jun'87	12.0	$0.15^{*}10^{-2}$	$0.13^{*}10^{-4}$	$0.11^{*}10^{-4}$	$0.48^{*}10^{-4}$	$0.48^{*}10^{-2}$	$0.74^{*}10^{-4}$	$0.27^{*}10^{-3}$	$0.43^{*}10^{-3}$
iii	18 Jun'88	09.8	$0.28^{*}10^{-4}$	$0.40^{*}10^{-4}$	$0.73^{*}10^{-4}$	$0.37^{*}10^{-3}$	$0.70^{*}10^{-3}$	$0.39^{*}10^{-3}$	$0.27*10^{-4}$	$0.79^{*}10^{-5}$
	17 Jun'88	01.5	$0.25^{*}10^{-2}$	$0.14^{*}10^{-3}$	$0.14^{*}10^{-3}$	$0.50^{*}10^{-3}$	$0.82^{*}10^{-3}$	$0.68^{*}10^{-3}$	$0.32^{*}10^{-3}$	$0.56^{*}10^{-4}$
iv	19-21 Aug'87	11.0 (Average)	$0.39^{*}10^{-4}$	$0.14^{*}10^{-4}$	$0.20^{*}10^{-4}$	$0.28^{*}10^{-4}$	$0.21^{*}10^{-4}$	$0.14^{*}10^{-3}$	$0.13^{*}10^{-3}$	$0.37^{*}10^{-5}$
	16-18 Aug'87	02.0 (Average)	$0.16^{*}10^{-2}$	$0.11^{*}10^{-3}$	$0.13^{*}10^{-3}$	$0.18^{*}10^{-3}$	$0.15^{*}10^{-3}$	$0.21^{*}10^{-4}$	$0.62^{*}10^{-5}$	$-0.11^{*}10^{-5}$
v	23-24 Jul'88	10.3 (Average)	$0.11^{*}10^{-2}$	$0.70^{*}10^{-5}$	$0.89^{*}10^{-5}$	$0.26^{*}10^{-3}$	$0.11^{*}10^{-2}$	$0.82^{*}10^{-3}$	$0.18^{*}10^{-4}$	$0.92^{*}10^{-6}$
	25-26 Jul'88	01.4 (Average)	$0.53^{*}10^{-4}$	$0.32^{*}10^{-5}$	$0.48^{*}10^{-5}$	$0.28^{*}10^{-4}$	$0.39^{*}10^{-4}$	$0.15^{*}10^{-3}$	$0.15^{*}10^{-3}$	$0.62^{*}10^{-5}$
vi	28-29 Sep'88	13.1 (Average)	$0.10^{*}10^{-2}$	$0.51^{*}10^{-4}$	$0.16^{*}10^{-4}$	$0.14^{*}10^{-4}$	$0.17^{*}10^{-4}$	$0.39^{*}10^{-5}$	$0.39^{*}10^{-5}$	$0.52^{*}10^{-5}$
	26-27 Sep'88	01.9 (Average)	$0.20^{*}10^{-2}$	$0.84^{*}10^{-4}$	$0.13^{*}10^{-3}$	$0.37^{*}10^{-3}$	$0.28^{*}10^{-3}$	$0.17^{*}10^{-4}$	$0.17^{*}10^{-4}$	$0.46^{*}10^{-4}$

4.4. Precipitable Water Content (PWC)

PWC for the individual case is given in Table 2. From the table we see that out of six cases under study in three cases PWC was more on the day of heavy rainfall and in three other cases PWC was more on the day of light spell. But the difference was not appreciable in any case. This is in close conformity with earlier findings of Srinivasan and Sadasivan (1975). They made a study using direct thermodynamic parameters and showed that moisture content in the lower tropospheric levels does not vary appreciably between weak monsoon and strong monsoon conditions.

4.5. *Scorer parameter (SP)*

Vertical Profiles of SP have been given in Figs.4(a&b) for a typical case (15th & 16th June 1987).

Scorer parameter at each layer (separated by 100 hPa) of the atmosphere is given in Table 3. From the table it can be seen that in every cases under study the value of SP, in the upper part of lower troposphere and in the middle troposphere, was more on light rainfall day than on heavy rainfall day.

4.6. *Stability*

Dry convective and moist convective instability have been examined from $\frac{\partial \theta}{\partial z}$ and $\frac{\partial \theta_e}{\partial z}$ profile. A typical vertical profile for contrasting rainfall epochs have shown in Figs. 3(a & b). In these figures $\frac{\partial \theta}{\partial z}$ and $\frac{\partial \theta_e}{\partial z}$ have been plotted against the mean height (above sea level) of each layer. So they represent the instability of each layer. It is seen that $\frac{\partial \theta}{\partial z}$ is positive at each layer in the atmosphere, which shows that atmosphere is dry convectively stable.

In Table 1weighted average values of static stability and convective instability, for six cases have been given.

From the table it is clear that in three cases weighted average value of static stability is more on the days of light rainfall and in rest of the cases it is more on the days of heavy rainfall. From the table we can also see that in four cases convective instability is more on the days of light rainfall which is again in close conformity with the earlier finding of Srinivasan and Sadasivan (1975).

Murakami (1977) introduced an index to measure the moist instability in the lowermost layer,

which is given by

$$Ie = \frac{\theta_{e_{850}} - \theta_{e_s}}{P_s - 850} \times 100 \qquad (9)$$

In our study we have used this index in slightly modified form, which is given as

$$Iem = \frac{\theta_{e_{900}} - \theta_{e_{1000}}}{1000 - 900} \times 100 \qquad (10)$$

Values of modified *Ie* are given in Table 1. From this table it can be seen that in three cases the moist instability at lowermost layer is more on the days of light rainfall and on the rest three days it is on the days of heavy rainfall.

4.7. *Zonal wind component (U)*

Vertical profile of U is given in Figs.2(a & b) for a typical case (7 and 8 July 1987). It has been observed that out of six cases under study, in four cases the strength of upper tropospheric easterly is more on the day of light spell, in one case it is more on the day of heavy spell and in one case it is almost same on two days.

It has been observed that in four cases the depth of the layer of atmosphere with westerly wind is less on the day of light spell than on the day of heavy spell.

This is in close conformity with the observation of Sarker (1966 & 67) where he had used a dynamical model of or ographical rainfall. It was observed by him that vertical profile of zonal wind, upstream of the ghat (Santacruz) had a larger (smaller) depth of monsoon westerly during strong (weak) monsoon condition.

4.8. *Lifting condensation level (LCL) and level of free convection (LFC)*

LCL and LFC for the contrasting situations in the different cases have been given in Table 2. From the table it can be seen that in three cases LCL was at a lower level on the day of heavy rainfall than on the day of less rainfall, in two cases it was at a lower level on the day of less rainfall and in one case LCL was at the same level on the two days of contrasting rainfall.

Also it is clear from the table that in most of the cases LFC was at a lower level on the day of heavy rainfall than on the day of light rainfall.

5. Conclusion

All the six cases have been studied in detail. Almost similar result have been observed. The salient features are given below :

(*i*) In most of the cases it has been observed that heavy rainfall over Mumbai during contrasting rainfall days is associated with one or more of the following synoptic situations on the day of heavy spell or one day before: (a) A trough on sea level chart running either from south Gujarat coast to Kerala coast or from Maharashtra coast to Kerala coast. (b) A CYCIR over Gujarat in the lower/middle tropospheric level. At least one of the above two systems and in some cases both of these ceased to exist on the day of light spell.

(*ii*) Initially MSE decreased with height, then attaining a minimum value, it started increasing with height. In most of the cases this minimum value of MSE is attained at a higher level on the day of light rainfall and also in most of the cases the weighted average value of MSE is more on the day of heavy rainfall.

(*iii*) In most of the cases it has been observed that strength of easterly at 200 hPa is much more on the day of light rainfall and also in most of the cases the depth of layers of westerly wind is less on the day of light rainfall.

(*iv*) In maximum cases CAPE is more on the day of heavy rainfall.

(*v*) PWC does not differ appreciably on the days of contrasting rainfall.

(*vi*) In most cases weighted average value of convective instability is more on light rainfall days.

(*vii*) In some cases lower most layer is more convectively unstable on the days of heavy rainfall and in other cases it is more on the days of light rainfall.

(*viii*) In the upper part of lower tropospheric layer and in the middle tropospheric layer, scorer parameter is about one order of magnitude greater on the day of light rainfall than on the days of heavy rainfall.

(*ix*) In most of the cases LFC is at a lower level on the day of heavy rainfall than on the day of light rainfall.

Acknowledgement

The authors are grateful to Dr. S.K. Dikshit, DDGM(WF) and Dr. A.B. Mazumdar, Director for their constant encouragement. Helpful discussion with Shri P.V.Pillai, Met-I regarding computer support is also acknowledged. We are also thankful to Mrs. V.V. Patekar, Mr. S.C. Nanaware, Mr. S.J. Gove, Mr. A.R. Murudkar, Mr. Robert Kalanke, Mr. B.S.Hirve and Mrs. Reshma for helping us in preparation of graphics for this paper.

References

Ananthkrishnan, R., Selvam, M. Mary, Chellappa, R., 1965, "Seasonal variation of Precipitable Water Vapour in the Atmosphere over India", *Indian J. Meteor. Geophys.*, **16**, 3, 371- 384.

Malkus, T.S., 1960, "Recent developments in the studies of Penetrative convection and an application to hurricane cumulonimbus towers", Cumulus Dynamics, New York, Pergamon Press, 65-84.

Malkus, J.S. and Ronne, C., 1954, "On the structure of some cumulonimbus clouds which penetrated in the high tropical troposphere", *Tellus*, **6**, 351-366.

Malkus, J.S. and Reihl, H., 1964, "Cloud structure and distributions over the tropical Pacific Ocean", Berkelay and Los Angeles, California : University of California Press.

Murkami, M., 1977, "On the structure of monsoon lows over the Inland area of northern India", *J. Meteor. Soc. Japan*, **55**, August, 442-448.

Mukherjee, B.K., and Ramana Murty., BH.V., 1978, "Features of lower troposphere on occasions of contrasting rainfall at a tropical coastal station", *Tellus*, **30**, 110-116.

Riehl, H., 1954, "Tropical Meteorology", New York: McGraw Hill Book Company, Inc.

Riehl, H., Cruz, L., Mata, M. and Muster, C., 1973, "Precipitation characteristics during the Venezuelan rainy season, "*Quart J. Royal Meteor. Soc.*, **99**, 746-757.

Sarker, R.P., 1966, "A dynamical model of orographic rainfall", *Monthly Weather Review*, **94**, 9, 555-572.

Sarker, R.P., 1967, "Some modifications in a dynamical model of orographic rainfall", *Monthly Weather Review*, **95**, 10, 673-684.

Sarker, R.P., Sinha Ray, K.C., De, U.S., 1978, "Dynamics of orographic rainfall.", *Indian J. Meteor. Geophys.*, 348.

Srinivasan, V. and Sadasivan, V., 1975, "Thermodynamic structure of the atmosphere over India during southwest monsoon season.", *Indian J. Meteor. Geophys.*, **26**, 169-180