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Features of lower troposphere on occasions of contrasting rainfall at a tropical coastal station

By B. K. MUKHERJEE and BH. V. RAMANA MURTY, *Indian Institute of Tropical Meteorology, Ramdurg House, University Road, Poona—411 005 India*

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ABSTRACT

The radiosonde data and the synoptic situations relating to pairs of consecutive days of contrasting rainfall recorded at the tropical coastal station, Bombay, were analysed for two contrasting summer monsoons. The synoptic situations relating to the pairs of days were classified into two categories, namely, not similar and nearly similar. The results pointed out that the majority of the higher rainfall days in the pairs, irrespective of the similarity in the synoptic situation, were associated with one or more of the following: (i) higher static stability, (ii) lower convective instability, (iii) higher precipitable water content and (iv) lower lifting condensation level.

The associations noted with (i) and (iii) were not statistically significant on both the categories of synoptic situations. The association with (ii) was significant at the 10% level when the synoptic situations were nearly similar and was not significant when the situations were not similar. The association with (iv) was significant at the 5% level on both categories of days. The features noticed were discussed in the light of the available knowledge for tropical oceanic and land regions.

1. Introduction

Studies reported about precipitation activity and the associated thermodynamic behaviour of the atmosphere over tropical oceanic and land regions (Riehl, 1954; Malkus and Ronne, 1954; Malkus, 1960; Malkus and Riehl, 1964; Riehl et al., 1973) have revealed a number of interesting features. Days associated with less or no precipitation activity do not contain less moisture than the days with good rainfall. Spectacular cumulonimbus may grow even in the face of a relatively dry atmosphere above 3 km. The lapse rate may be more unstable with a sky of widely separated, stunted trade cumulus than when towering cumulonimbus is rampant as in hurricane.

The studies which revealed the above features were mostly confined to the Caribbean and the Pacific regions in the tropics. It is not known whether similar features would also obtain in the Indian tropics, although some interesting aspects of the monsoon activity in this region were reported (Ramage, 1971). As part of an attempt to examine the rainfall features and the associated thermodynamic behaviour with respect to the Indian region, a study has been undertaken for the tropical coastal station, Bombay (18° 54′ N, 72° 49′ E). The results obtained are presented below.

2. Conditions of cloud and rain at Bombay

Bombay receives nearly 91% of its annual total rainfall of 1804.8 mm during the summer monsoon, June to September. Vigorous convection occurs at the station during this period and the weather is controlled by the passage of innumerable convective cells. A comprehensive study reported on the aspects of convective activity at Bombay (Bhaskara Rao and Dekate, 1971) and pointed out the interesting feature that, in spite of the increase of rainfall in the months of July and August, there is a sharp decrease in thunderstorm activity—a feature which is unusual for the tropical latitudes. The cloud tops at Bombay and neighbourhood, as also confirmed by the radar observations, generally extend only to about 5 km on most of the heavy rain days. The rains, particularly along the west coast of India, are notable for a dearth of thunderstorms (Ramage, 1971).

The main synoptic systems which are associated with active monsoon conditions over the Bombay region are:

(i) trough of low pressure off the coast on the surface chart and in the low levels,
(ii) formation of depression or low over North Bay of Bengal and its movement in a westerly direction across the country, and
(iii) upper air cyclonic circulation over the Konkan and Gujarat, particularly between 700 and 500 mb.

3. Analysis

The study made is restricted to pairs of consecutive days associated with contrasting amounts of rainfall at the station. Consecutive days were chosen to constitute a pair in order to minimize the variation in the synoptic situation influencing the weather at the station on the days in the pair. The periods considered for the study are the summer monsoons of 1964 and 1966 which were respectively good and bad monsoon years for the Indian sub-continent. The total number of pairs of days available during these two monsoons was 29. These pairs of days were classified into two categories depending upon whether the synoptic situations on the days in the pair were nearly or were not similar.

The aspects considered in the study are (i) precipitable water content (gm cm^{-2}), (ii) stability (m^2 mb^{-2} s^{-2}), (iii) height of the lifting condensation level (mb) and (iv) synoptic situation. These were analysed for the days in all the pairs. The values of precipitable water content and stability were evaluated from the mean data of the radiosonde soundings of 00 and 12 GMT for the station. The evaluations were done at intervals of 100 mb up to 500 mb, the level up to which dew point temperature reported is considered reliable. The height of the lifting condensation level was evaluated from the mean data of radiosonde soundings. The synoptic situation was assessed from the daily 12 GMT meteorological charts.

(I) The precipitable water content in the column of air from surface to 500 mb level is given by

$$W = -\frac{1}{g}\int r\,dp$$

where r is the mixing ratio in grams per kilogram of dry air and p is the pressure in millibars. The pressure difference considered was 100 mb.

(II) Using eq. (7) of Gates (1961) and by suitable transformation, the stability value is given by

$$\sigma = \frac{\partial\phi}{\partial p}\cdot\frac{\partial}{\partial p}(\ln\theta)$$

Here ϕ is the geopotential in meters, p the pressure in millibars and θ the potential temperature in degrees absolute. The static stability was computed by using the values of dry bulb potential temperature for θ. The convective or conditional instability was calculated by using the value of equivalent potential temperature for θ. The weighted mean values of the stability $\bar{s}$ were computed by using the expression

$$\bar{s} = \frac{\sum_{i=1}^{5} s_i z_i}{\sum_{i=1}^{5} z_i}$$

where s_i (i = 1 to 5) and z_i (i = 1 to 5) are the values of the stabilities and heights respectively in the interval surface to 900, 900 to 800, 800 to 700, 700 to 600, and 600 to 500 mb.

(III) The height of the lifting condensation level was evaluated from the mean data of radiosonde soundings for the days in question. This was done following Haltiner and Martin (1957).

(IV) The synoptic situations were assessed for the days in all the pairs based on the 12 GMT surface and upper air charts.

The Wilcoxon matched-pairs signed-ranks two-tailed statistical test (Walker and Lev, 1953; Siegal, 1956) was applied on the values obtained for the parameters (I), (II) and (III) referred to above. The values were considered statistically significant, unless otherwise mentioned, if they were found significant at the 5% level or less.

Table 1. *Values of thermodynamic parameters on pairs of days when synoptic situations are not similar. Dates with higher precipitable water content associated with lower rainfall are shown by asterisk*

Date	Precipitable water content ($g\ cm^{-2}$)	Lifting condensation level (mb)	Static stability × 10^4 ($m^2\ mb^{-2}\ s^{-2}$)	Convective instability × 10^4 ($m^2\ mb^{-2}\ s^{-2}$)	Rainfall (mm)
14 June 64	5.68	985	218.3	−71.7	91.7*
15 June 64	6.18	960	223.5	−54.3	6.0
5 July 64	5.91	978	229.7	−71.1	85.2
4 July 64	4.92	960	229.3	−67.7	4.8
17 July 64	4.24	950	184.9	−101.0	28.5*
16 July 64	6.13	960	238.6	−67.0	0.2
20 July 64	5.27	950	216.9	−71.9	27.8
19 July 64	5.09	953	210.6	−106.0	2.4
11 Aug. 64	5.52	980	245.7	−83.2	89.3*
10 Aug. 64	6.04	968	243.0	−13.2	14.5
12 Aug. 64	6.27	987	256.9	+21.5	58.4
13 Aug. 64	5.90	970	271.7	−37.4	7.3
30 Sept. 64	5.45	969	221.7	−57.6	112.1
29 Sept. 64	4.95	962	222.7	−74.5	0.0
18 June 66	6.23	960	253.5	−24.3	42.8
17 June 66	5.22	930	177.0	−164.3	0.0
27 Sept. 66	5.55	940	227.4	−54.7	40.2
26 Sept. 66	3.73	908	149.1	−71.5	0.0

4. Results

4.1. *Synoptic situations not similar on the days in the pair*

The synoptic situations on the consecutive days in the pairs were not similar in 7 pairs in 1964 and in 2 pairs in 1966. Analysis made with respect to these 9 pairs pointed out the following.

(i) *Precipitable water content* (*PWC*). The values of precipitable water content and 24 hours' rainfall are given in columns 2 and 6 of Table 1. The PWC was less in three of the higher rainfall days in the 9 pairs. The decrease in PWC on such days ranged up to 31%. The difference in PWC between the days of contrasting rainfall is not significant.

(ii) *Stability* (σ). The weighted mean values of static stability and convective instability are given in columns 4 and 5 respectively.

The static stability was more and convective instability was less in five of the higher rainfall days in the pairs. The increase in static stability and the decrease in convective instability on such days ranged respectively up to 52.5 and 157.5%. The difference in static stability between the days of contrasting rainfall is not statistically significant; so also is the difference in convective instability.

(iii) *Height of the lifting condensation level* (*LCL*). The values of the height of lifting condensation level are given in column 3. The LCL was higher in two of the higher rainfall days in the pairs. The increase in the LCL ranged up to a depth equivalent of 10 mb. The difference in the LCL between the days of contrasting rainfall is significant.

4.2. *Synoptic situations nearly similar on the days in the pair*

The synoptic situations on the consecutive days in the pairs were nearly similar in 8 pairs in 1964 and in 12 pairs in 1966. Analysis made with respect to these 20 pairs pointed out the following.

(i) *Precipitable water content* (*PWC*). The values of precipitable water content and 24 hours' rainfall are given in columns 2 and 6 of Table 2. The PWC was less in seven of the higher rainfall days in the 20 pairs. The decrease in PWC on such days ranged up to 17%. The difference in PWC between the days of contrasting rainfall is not significant.

(ii) *Stability* (σ). The weighted mean values of static stability and convective instability are given in columns 4 and 5 respectively.

The static stability was more and the convective

Table 2. *Values of thermodynamic parameters on pairs of days when synoptic conditions are nearly similar. Dates with higher precipitable water content associated with lower rainfall are shown by asterisk*

Date	Precipitable water content ($g\ cm^{-2}$)	Lifting condensation level (mb)	Static stability × 10^4 ($m^2\ mb^{-2}\ s^{-2}$)	Convective instability × 10^4 ($m^2\ mb^{-2}\ s^{-2}$)	Rainfall (mm)
12 June 64	5.50	965	257.9	−72.9	38.1
11 June 64	5.44	939	246.4	−55.9	0.0
22 June 64	5.70	975	198.4	−108.6	94.4
21 June 64	5.56	961	207.4	−83.4	0.2
22 June 64	5.70	975	198.4	−108.6	94.4*
23 June 64	6.28	970	247.0	−9.7	17.5
17 July 64	4.24	950	184.9	−101.0	28.5*
18 July 64	5.13	957	226.4	−38.4	0.8
7 Aug. 64	5.65	978	247.1	−5.9	38.0
8 Aug. 64	5.54	969	256.8	−14.5	1.1
13 Sept. 64	5.03	968	253.6	+7.3	21.5*
12 Sept. 64	5.79	980	231.5	−75.4	5.5
15 Sept. 64	6.13	965	247.3	−5.0	16.5
16 Sept. 64	5.64	977	213.1	−94.9	0.4
18 Sept. 64	6.02	972	234.1	−45.3	51.2
17 Sept. 64	5.42	968	230.4	−95.5	1.5
9 June 66	6.02	968	207.4	−102.9	28.8
8 June 66	5.72	925	175.1	−140.9	2.6
14 June 66	5.87	992	240.6	−67.0	79.7
15 June 66	5.53	949	170.7	−161.3	10.8
18 June 66	6.23	960	253.5	−24.3	42.3
19 June 66	5.93	920	241.5	−100.0	1.3
13 July 66	6.08	968	230.8	−14.4	31.3
12 July 66	5.71	938	230.9	−72.6	3.5
27 July 66	6.30	972	300.1	+59.9	42.6
28 July 66	5.59	967	263.8	−47.4	4.8
14 Aug. 66	5.65	954	286.4	−6.5	20.9
13 Aug. 66	4.97	947	285.0	−72.1	0.0
16 Aug. 66	5.87	962	243.1	−40.1	20.2
17 Aug. 66	5.48	950	242.7	−19.4	1.4
18 Aug. 66	5.01	970	254.1	−55.3	18.1*
17 Aug. 66	5.48	950	242.7	−19.4	1.4
18 Aug. 66	5.01	970	254.1	−55.3	18.1*
19 Aug 66	5.34	960	306.1	−92.6	2.3
24 Sept. 66	4.47	950	215.8	−81.2	27.3
23 Sept. 66	5.39	932	192.4	−45.2	1.1
24 Sept. 66	4.47	950	215.8	−81.2	27.3
25 Sept. 66	4.54	948	213.4	−103.9	0.0
27 Sept. 66	5.55	940	227.4	−54.7	40.2
28 Sept. 66	5.29	938	243.4	−3.3	0.0

instability was less in 13 and 12 cases respectively of the higher rainfall days in the pairs. The increase in static stability and the decrease in convective instability on such days ranged respectively up to 41 and 226%. The difference in static stability between the days of contrasting rainfall is not significant. But the difference in convective instability is significant at the 10% level.

(iii) *Height of the lifting condensation level (LCL).* The values of the height of the lifting condensation level are given in column 3. The LCL was higher in three of the higher rainfall days in the pairs. The increase in the LCL ranged up to a depth equivalent of 12 mb. The difference in the LCL between the days of contrasting rainfall is significant.

5. Discussion

The thermodynamic features of the lower troposphere over the coastal station Bombay were examined for pairs of consecutive days of contrasting rainfall. An attempt was made to compare these features with those reported for the atmosphere over the Caribbean and over the tropical Pacific regions. In doing so the higher and lower rainfall occasions in the present study are likened to the occasions of cumulonimbus growth and of stunted cumulus growth respectively over those regions. The present study pointed out that the behaviour of the atmosphere in the lower troposphere over the Bombay region was, in certain respects, similar to what was reported for that over the Caribbean and the Pacific regions.

The static stability was higher and the convective instability lower on the higher rainfall days in the majority of the pairs of days. The features observed are generally in conformity with what were reported for the Caribbean and the Pacific regions. Also the difference in convective instability noted in the present study on the days of contrasting rainfall in the pairs is statistically significant at the 10% level when the synoptic situations on both the days in the pairs were similar. The precipitable water content was higher on the higher rainfall days in the majority of the pairs. But on some occasions of lower rainfall, the precipitable water content remained high. These features are in conformity with what were found to be the case on some occasions over the tropical Pacific. The height of the lifting condensation level was significantly low, as was anticipated, on the higher rainfall days in the majority of the pairs.

The pairs of days were grouped into two categories depending upon whether the synoptic situations on the consecutive days in the pairs were or were not similar. The analysis pointed out that the situations were nearly similar in the majority (69%) of the pairs. Also, the behaviour of stability, precipitable water content and lifting condensation level were nearly alike on both the categories of pairs of days.

The feature of higher static stability on the majority of the days of higher rainfall, although not statistically significant, is not what is normally anticipated. A similar feature was reported over the Caribbean on the days when Hurricane Daisy formed (Malkus, 1960). The static stability on those days was 25% higher than what it was under average conditions wherein no penetrative development occurred. Penetrative convection plays a dominant role in the development of large cumulus and cumulonimbus towers. This feature of convective motion could substantially alter the temperature structure of the layer (Musman, 1968). Presumably, the higher static stability noted on the majority of the days of higher rainfall would have been modified favourably for incidence of higher rainfall. Also, on higher rainfall days the lower troposphere remains uniformly moist as compared with lower rainfall days, so much so that the gradient of mixing ratio on the former occasions may be less than on the latter. Such a feature should result in less convective instability on higher rainfall days as was indicated in the present study. Although the tropical atmosphere is usually conditionally unstable in the lower troposphere, this instability does not always become the prime factor for cloud growth, much less for the growth of cumulonimbus. For these reasons it is considered that the instability factor has failed to indicate its unique significance in precipitation development. On the contrary, synoptic scale convergence in the friction layer enhances total rainfall through massive ascent, but by increasing the depth of moist air and diminishing the lapse rate, hinders thunderstorm development (Ramage, 1971). Studies reported (Charney and Eliassen, 1964; Holton, 1972) have shown that the low level convergence in convective-scale, responsible for cumulonimbus formations, is induced by synoptic-scale disturbances. In fact, the motion in the convective-scale and in the synoptic-scale interact co-operatively. The former supplies the heat necessary to drive the synoptic-scale disturbances and the latter the moisture necessary to drive the motion in convective-scale. An observational study of rainfall activity over south Florida (Fernandez-Partagas and Estoque, 1974) has revealed that larger scale convergence produces smaller scale convergence which in turn induces rainfall. Also, the importance of cloud interaction for formation of a tornado has been brought out in a recent observational study over Florida using close meso-network (Holle and Maier, 1976). It is pointed out that the interaction of the downdrafts emanating from strong, antecedent thunderstorm clouds can form a tornado against unfavourable conditions such as neutral stability and weak synoptic condition.

The height of the lifting condensation level was significantly lower on the days of higher rainfall. This is consistent with what is anticipated, for moist parcel becoming saturated at a lower level is a precondition for development of cloud to a greater depth.

In so far as the values of the precipitable water content are concerned, these are higher, as expected, on the majority of the higher rainfall days. But the difference in the values between higher and lower rainfall days in the pairs is not significant. On some occasions of lower rainfall, the precipitable water content remained high (Vide, dates with asterisk in the tables). Such a feature was also reported over the tropical Pacific ocean even after the suppression of cloudiness. It was thought (Malkus and Riehl, 1964) that dynamic factors producing even slight damping of convective activity through subsidence are of much greater importance in determining the cloud types and their distribution than is the total water content of the atmosphere.

6. Conclusion

The thermodynamic behaviour of the lower troposphere on consecutive days of contrasting rainfall was examined for the station Bombay, situated on the west coast in a region of vigorous monsoon activity. The study has revealed the following features.

(i) Higher static stability, less convective instability and higher precipitable water content were found on the majority of higher rainfall days. These are in line with the findings reported over the Caribbean and the tropical Pacific. Higher precipitable water content found on some occasions of lower rainfall days is also in line with what was reported to be the case on some occasions over the tropical Pacific (Malkus and Riehl, 1964).

(ii) The differences in static stability and in precipitable water content between the consecutive days of contrasting rainfall, irrespective of the similarity in the synoptic situations on such days, are not significant. But the differences in convective instability on such pairs of days is significant at the 10% level, when both the days in the pairs are under similar synoptic situations.

(iii) The heights of the lifting condensation level were significantly lower on the higher rainfall days.

The present study, which is restricted to the coastal station Bombay, is a preliminary attempt to understand to what extent the atmospheric features noted over the tropical Caribbean and the Pacific regions are valid for the Indian region. The study has to be extended to other representative regions of the country before definitive conclusions become possible.

REFERENCES

Bhaskara Rao, N. S. and Dekate, M. V. 1971. The effect of vertical wind structure on some aspects of convective activity at Bombay. *Indian J. Meteor. and Geophys. 22*, 59–66.

Charney, J. G. and Eliassen, A. 1964. On the growth of the hurricane depression. *J. Atmos. Sci. 21*, 68–75.

Gates, W. L. 1961. Static stability measurements in the atmosphere. *J. Meteor. 18*, 526–533.

Fernandez-Partagas, J. J. and Estoque, M. A. 1974. An observational study of convergence and rainfall over south Florida. *J. Appl. Meteor. 13*, 507–509.

Haltiner, G. J. and Martin, F. L. 1957. *Dynamical and physical meteorology*. New York: McGraw-Hill Book Company, Inc., pp. 33–34.

Holle, R. L. and Maier, M. W. 1976. *Cloud interaction and the formation of the 15 June 1973 Tornado in the FACE mesonetwork*. NOAA Technical Memorandum ERL WMPO-33, National Oceanic and Atmospheric Administration, U.S. Dept. of Commerce, Coral Gables, Fla.

Holton, J. R. 1972. *An introduction to dynamic meteorology*. International Geophysics Series, Vol. 16. New York: Academic Press.

Malkus, J. S. 1960. Recent developments in studies of penetrative convection and an application to hurricane cumulonimbus towers. In: *Cumulus dynamics*. New York: Pergamon Press, pp. 65–84.

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

Mulkus, J. S. and Riehl, H. 1964. *Cloud structure and distributions over the tropical Pacific Ocean*. Berkeley and Los Angeles, California: University of California Press.

Musman, S. 1968. Penetrative convection. *J. Fluid Mechanics 31*, part 2, 343–360.

Ramage, C. S. 1971. *Monsoon meteorology*. International Geophysics Series, Vol. 15. New York: Academic Press.

Reihl, 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. Roy. Meteor. Soc. 99*, 746–757.

Siegel, S. 1956. *Non-parametric statistics for the behavioral sciences*. New York: McGraw-Hill Book Company, Inc.

Walker, H. M. and Lev, J. 1953. *Statistical inference*. New York: Henry Holt and Company, Inc.

ОСОБЕННОСТИ НИЖНЕЙ ТРОПОСФЕРЫ В СЛУЧАЯХ КОНТРАСТИРУЮЩИХ ВЫПАДЕНИЙ ДОЖДЯ ДЛЯ ТРОПИЧЕСКОЙ ПРИБРЕЖНОЙ СТАНЦИИ

Для двух контрастирующих летних муссонов анализировались радиозондовые данные и синоптические ситуации, относящиеся к парам последовательных дней с различными осадками, регистрировавшимися на тропической прибрежной станции Бомбей. Синоптические ситуации, относящиеся к парам дней классифицировались по двум категориям, именно, различные и близко похожие. Результаты указывают, что большинство дней с высокими осадками в парах, независимо от сходства в синоптической ситуации, связаны с одним из следующих обстоятельств или с некоторыми из них вместе: 1) повышенная статистическая устойчивость, 2) пониженная конвективная неустойчивость, 3) большее содержание сконденсированной воды и 5) меньшие поднятия уровня конденсации.

Связи, отмеченные с явлениями 1) и 3) не были статистически значимыми для обеих категорий синоптических ситуаций. Связь с 2) была значимой на 10 %-ном уровне, когда синоптические ситуации были сходными, и не была значимой, когда ситуации были различными. Связь с 5) была значимой на 5 %-ном уровне для обеих категнрий дней. Отмеченные особенности обсуждаются в свете доступных данных для тропических областей океана и суши.