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Rainfall probabilities and amounts associated with monsoon depressions over India

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सार — 24 घण्टे की वर्षा की प्रायिकताओं के बितरण का मिश्र संचित्र, जो 2.5 मि. मी. तथा 65 मि. मी. केबराबर अथवा अधिक होता है, भारत के ऊपर पिछले 24 घण्टों में वर्षा की औसत मात्रा, अवदाबों की विभिन्न भौगोलिक स्थितियों के लिये 16 वर्ष की अवधि के लिये 220 केन्द्रों के दैनिक वर्षा आंकड़ों का उपयोग करके निर्धारित की जाती है। पांच स्वतंत्र वर्षों में 12 केन्द्रों पर वर्षा प्रायिकता का पूर्वानुमान जारी करने के लिये वर्षा प्रायिकता के मिश्र संचित्रों का उपयोग किया जाता है। उपयुक्त द्विघात समांकों द्वारा मूल्यांकन करने पर इन पूर्वानुमानों ने 10 % निपुणता अंक (स्किल स्कोर) दिखाया।

ABSTRACT. Composite charts of distribution of probabilities of 24-hr rainfall amounts ≥ 2.5 mm and ≥ 65 mm and the average 24-hr rainfall amounts over India are determined for various geographical locations of the depressions by using daily rainfall data of 220 stations for a 16-year period. The composite charts of rainfall probabilities are used to issue forecasts of probability of rain at 12 stations during five independent years. These forecasts when evaluated by a proper quadratic score showed skill score of 10%.

1. Introduction

It is well known that even during the period of established monsoon the day-to-day circulation and the associated rainfall distribution undergoes dramatic change from little rainfall to abundance of rainfall over India. As the large scale rainfall distribution over the country is mainly controlled by the synoptic systems, the forecaster formulates the forecast of the expected areal coverage of rainfall over various parts of the country from the empirical knowledge and some dynamical principles about the formation, intensification, decay and movement of the circulation systems and the associated rainfall distribution. In this formulation he is guided by the published literature on the above mentioned synoptic climatological aspect of the monsoon circulation and rainfall and his own past experience about the behaviour of circulation systems. It is desirable that the knowledge about the rainfall distribution around various synoptic systems is objectivised and is made available to the forecaster in the form compatable with his mode of expression of forecasts. The most suitable way, in which rainfall distribution around or due to circulation systems over larger parts of the country can be presented is compositing. Apart from their obvious use as an aid in operational forecasting, it is believed that such composite charts shall be useful for (*i*) extending the enquiries into the physical mechanism responsible for particular type of distribution of rainfall and (*ii*) verification of results of medium range prediction or simulation of circulation and weather fields by numerical models. The similar synoptic systems needed for compositing can be identified either by comparing the entire distribution of some meteorological field(s) over the region of interest or by comparing location and other features of some prominent circulation systems. The latter approach is followed in the present study. Since the monsoon depressions are one of the most important rain producing agencies and they undergo somewhat orderly movement over the Indian region during the monsoon season, the study is confined to these synoptic systems only.

1.1. *An overview of past studies*

Pisharoty and Asnani (1957) were the first to present a composite picture of heavy rainfall (≥ 6.5 cm in 24-hr) distribution based on rainfall data for 4 monsoon depressions. They found that the heavy rainfall occurs upto 1000 km ahead of the depression centre and upto 400 km to the left of depression track. Raghavan (1967) studied the spatial distribution of percentage deficiency in the monthly rainfall of July and August caused by the absence of monsoon depressions. Mooley (1973) studied the spatial distributions of mean 24-hr rainfall within 500 km of the 24-hr mean positions of the depressions centred around 87 deg. E, 80 deg. E and 75 deg. E longitudes. He noted that the maximum rainfall is

located about 150 km ahead of the 24-hr mean centre of the depression or about 300 km from the centre of the depression at the beginning of the 24-hr period for which rainfall has been considered and between 50 and 150 km to the left of the track of depression. He further pointed out that the heavy rainfall extends only upto 250 km south and upto 500-600 km ahead of the depression position at the beginning of the 24-hr period. Further, from the analysis of average rain per depression day, standard deviation of depression rain and the contribution of depression rain to the total rain for the three-longitude sector, he established that the mean rainfall per depression day in the left sector of depression increases westward. Dhar and Mhaiskar (1973), after compositing the rainfall distribution around 10 depressions crossing the Orissa coast, found that the heavy rainfall occurs over a strip with its boundaries 40 to 120 km south of the track of depression. Recently Chowdhary and Gaikwad (1983) have also arrived at similar conclusions about the distribution of 24-hr rainfall around the depression by using data of 540 rainfall stations and 27 depression cases.

1.2. *Scope of the present study*

All studies mentioned above have identified the areas receiving heavy rainfall with respect to the location of monsoon depressions by analysing the spatial distribution of the maximum mean and heavy rainfall during the 24-hr period. No composite charts for the probability of occurrence of rainfall or heavy rainfall have been presented. Thus, although the hitherto published composite charts guide the forecaster to delineate the areas expected to receive heavy rainfall, there is no guidance available about the probability of occurrence of rain over the area affected by the depression. Most of the previous studies have considered the rainfall occurrence within 500 km of the daily mean position of the depressions. It has been pointed out by some workers (*e.g.*, Mukherjee and Shyamala 1978) that the influence of depressions in causing rainfall extends beyond 500 km. Thus it seems to be necessary that the climatic characteristic of the rainfall over the whole country is studied for the cases of depressions. Further no study seems to have verified the utility of the composite rainfall charts in actual forecasting. The principal objective of the present study is to present the composite charts of the distribution of probability of rainfall $\geqslant 2.5$ mm and $\geqslant 65$ mm during the peak monsoon months (*i.e.*, July and August) such that they provide probabilistic guidance to the forecasters for the occasions when a depression is present over the country. The utility of these composites is verified on independent sample by using proper scores.

2. Data

Daily rainfall data of 220 stations (Fig. 1) evenly distribution over India were collected for July and August for 16 years (1958 to 1973) from the India Meteorological Department. The rainfall data of 12 of these stations were extended by 5 years, *i.e.*, upto 1978, to create an independent sample needed for the verificaton of the utility of the rainfall conposite charts. Locations of depressions (or deep depressions) at 03 GMT were taken from the India Meteorological Department (IMD) publication "*Tracks of storms and depressions*" (IMD 1979).

3. Methodology

At first the frequencies of occurrence of depressions during the sixteen years period are determined for each of the twenty-two 2.5° Lat./Long. blocks (Fig. 2). For determining the composite picture of rainfall due to the depressions, a computerised moving grid method similar to that of Jorgensen (1963) is adopted. The centre of a 14° Lat./20° Long. rectangular grid of mesh size 1° Lat./Long. is assumed to be placed (in the computer memory) on the centre of the depression, located within a particular geographical block (*see* Fig. 2), with the x-axis of the grid oriented along the latitude circle. Rainfall stations falling in each of the 280 (14 × 20), 1° Lat. × 1° Long. squares of the grid are identified and the occurrence of the three types of rain events, *viz.*, rain $\geqslant 2.5$ mm, $\geqslant 10$ mm and $\geqslant 65$ mm and the actual rain amount during the 24-hour period are noted and stored squarewise in the computer memory alongwith the number of stations which fell in each square. All these rainfall parameters, *viz.*, (*i*) number of occurrences of rain events defined for the three different thresholds, (*ii*) actual rainfall amount and (*iii*) the number of stations falling in each square, are accumulated over all the depression cases for which the depression centres lay in a particular geographical block. The probabilities of occurrence of rain events (for each of three thresholds) are then determined for each square by dividing the number of accumulated rain events by the accumulated number of stations which fell in the particular square. Likewise the average 24-hr rain amount in each square is determined by dividing the accumulated rain amounts by the accumulated number of stations which fell in the particular square. The above types of composites (henceforth to be referred as moving grid composites) are prepared for each of the 22 geographical blocks.

Since the above moving grid could not capture the distant effects (*e.g.*, Mukherjee and Shyamala 1978) of the depressions in producing rain, we determined the similar rainfall statistics for each of the 220 rainfall stations by considering the days when the depression centre lay in particular geographical block. This type of compositing, (to be referred below as station composites) was also done for all 22 geographical blocks. A total of about 100 composite charts of different types are prepared but only a few composites, which are based on sufficient number of depression cases are presented and discussed in section 4 below. The climatic probabilities of occurrence of rainfall at stations in each month (needed below) are determined by using the same 16 years (1958-1973) of data.

The choice of the three types of rain events is governed by the following consideration. A day is officially considered as rainy day (heavy rainfall day) by the India Meteorological Department if the 24-hr rainfall on the day equals or exceeds 2.5 mm (65 mm). The official forecasts predict the likely occurrence of rain events equalling or exceeding these two thresholds.
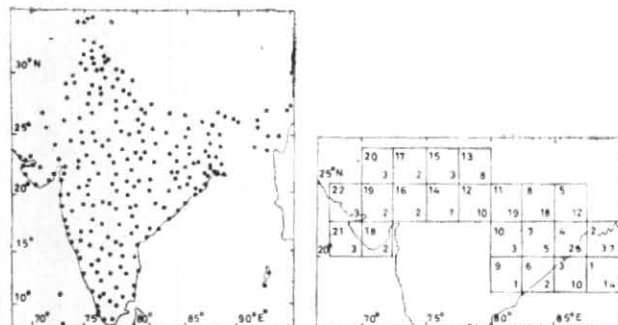
Fig. 1   Fig. 2

Dots represent the rainfall stations used in this study (Fig. 1).
Frequencies of occurrence of depressions in 22/2.5°
Lat./Long. blocks during July-August of 16 years
(1958-73). The numbers in the top left corners repre-
sent the serial number of the blocks and in the right
bottom corners represent the frequencies of depres-
sions (Fig. 2)

In the discussion which follows the terms probability
of occurrence of rainy days (heavy rainfall days) will
refer to the above amounts respectively and the compo-
site charts will be presented for these two types of
rain events only. In general the average rainfall per
day during the peak monsoon months (i.e., July and
August) over the major parts of the country is near
1 cm. Hence this additional threshold was also consi-
dered in the present study. The composite charts for
this threshold are not presented as this threshold does
not form a component in the official forecasts. We
have, however, used the composites corresponding to
this threshold for verifying the utility of the compo-
sites in issuing the forecasts on independent sample.

4. Results and discussion

The probabilities of rain days and heavy rain days
and the average rain amount recorded during the 24-hr
periods are presented in Figs. 3(a, b & c) respectively
for selected six blocks only which lie along the main
track of the depressions (Dhar and Ghose 1972) and
have sufficient frequencies of depression cases. The
probability of rain days exceeds 0.8 ahead of the
depression, over an area varying from 3 to 5 deg. Lat.
width and 5 to 10 deg. Long. in length (1 deg. Long.
≃ 100 km) depending on the geographical positions
of the depression. Over half of this area the probability
of rain exceeds 0.9 when the depressions are centred
to the east of 80 deg. E longitude. The probability
of rain day is found to be more than the climatic
probability over the area lying ahead of the depression
upto the westernmost boundary of the country. Far
north and south of the depression track the probabi-
lity of rainy days is less than the climatic probability
(e.g., see Fig. 4). Thus the depressions do not enhance
the probability of occurrence of rainy days over the
whole country but reorganise the rain occurrence in a
particular manner (see also Raghavan 1967). This
reorganisation (enhancement or reduction) of rain
probability is more extensive when the depressions lie

between 80 deg. longitude and the east coast (e.g.,
see the diagram corresponding to square 4 in Fig. 3a).
The probability of rainy days increases over Rajasthan,
Gujarat, west coast and adjoining Peninsula as soon as
the depression crosses 85 deg. E longitude thus support-
ing the results of Mukherjee and Shyamala (Loc. cit.).
The increase in probability of rainy days over the west
Rajasthan is not, however, more than 0.2 unless the
depression reaches near 80 deg. E. The probability
of rainy days is found to increase in the rear of the
northeast quadrant when the depression crosses the
82.5 deg. E longitude supporting Raghavan's (Loc.
cit.) results.

The probability of heavy rainfall exceeds 0.2 over
an area of about 2-3 deg. wide and 5-6 deg. long
lying to the south or more specifically southwest sector
of depression. As the depressions move west of 80
deg. E the extent of isopleth of probability 0.2 or 0.3
decreases but the probability of heavy rainfall in
isolated areas becomes quite high. Probability of heavy
rainfall over Gujarat and north Konkan increases signi-
ficantly as the depressions reach near 80 deg. E (see
also Abbi et al. 1970).

The average 24-hr rainfall exceeds 2 cm over a
rectangular belt 3-4 deg. wide and 7 to 10 deg. long.
Over an inner core, the average rainfall exceeds 4 cm.
This core of higher rainfall is more extensive when
the depressions lay in blocks 7, 8 and 12. There is
evidence of an anchored zone of heavier rainfall near
80 deg. E as observed by Bedekar and Banerjee (1967)
when the depression lies in the squares 5, 7 and 8.

The composite charts for the probability of rainfall
can directly be used as guidance for issuance of fore-
casts of expected areal coverage of rainfall over the
sub-divisions. It may be remembered that the simple
average of probabilities of rainy days over the stations
in a geographical area is equal to the expected areal
coverage of rainfall in the area. Thus the given proba-
bilities of rainy days for the individual stations or 1
deg. × 1 deg. grid squares can be easily transferred
into the expected areal coverage of the rainfall over
any geographical region, say a meteorological sub-
division. Likewise composite charts for the probability
of heavy rain days and the average expected rain
amount can be used as guidance for issuing the fore-
casts of respective aspects of rainfall over any geogra-
phical region.

5. Application of forecasting

5.1. The skill of forecasts

The probabilities of rain ($\geqslant 2.5$ mm and $\geqslant 10$ mm)
in 24-hr periods determined above are used to issue the
forecasts of rain occurrence over 12 stations on 76
depression days during the 5 years (1974-78) of indepen-
dent period. The results of forecasts in terms of proba-
bility score are given in Table 1. The probaility score

(PS) is given by : $\dfrac{1}{n} \sum_{i=1}^{n} (P_i - \delta)^2$, where P_i is the

forecast probability of rainy day and δ is 1 if the rain
event occurs and is 0 if the rain event does not occur
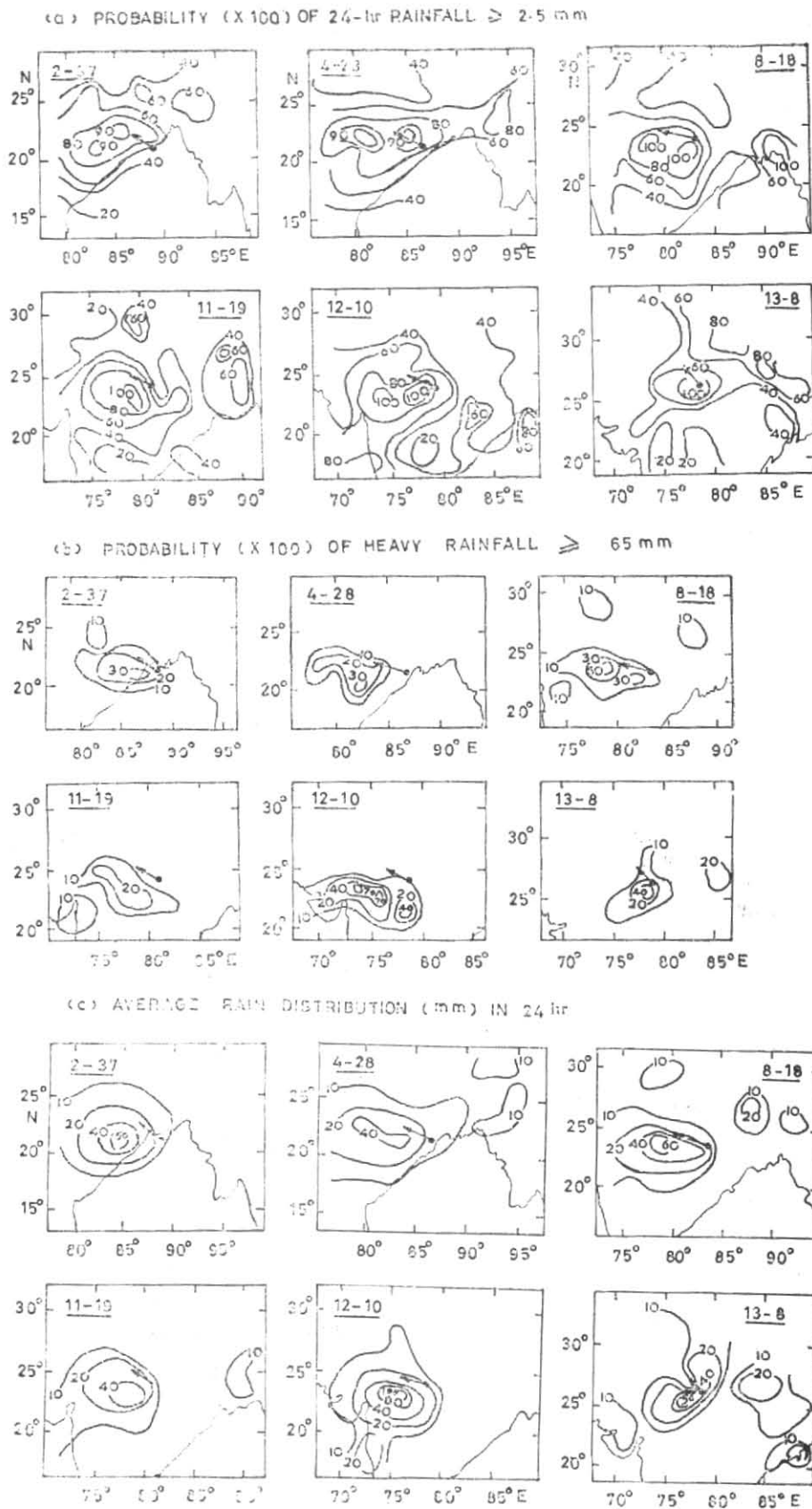
Figs. 3 (a-c). Probabilities (×100) of 24-hr : (a) rainfall (≥2.5 mm), (b) heavy rainfall (≥ 65 mm) and (c) Average rain distribution (in mm) in 24-hr period for various geographical locations of depressions in association with depressions located in various geographical areas. The first number on the right top corner represents the serial number of the blocks while the number following represents the frequencies of occurrence of depressions in the particular block. The average positions of the depressions in the block at the beginning of the 24-hr period is shown by a solid circle and at the end of the 24-hr period is shown by arrowhead.
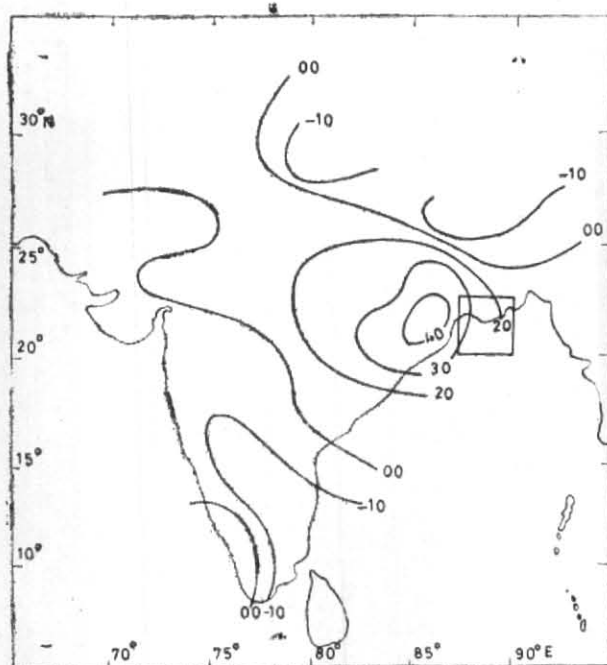
Fig. 4. Difference between probability of rainy days ($\geqslant 2.5$ mm) associated with depression *minus* the climatic probability, in percentage for the depressions lyin in block 2.

TABLE 1

Probability score for climatology and forecasts and skill scores in percentage for two thresholds, *viz.*, 2.5 mm and 10 mm of rainfall. Tne probability scores are rounded upto 2 decimal places and skill scores expressed in percentage are rounded up to integer number. Total number of forecasts is 76.

	Probability score		Skill score	Probability score		Skill score
	Clim.	F/C		Clim.	F/C	
	Rainfall $\geqslant 2.5$ mm			Rainfall $\geqslant 10$ mm		
Bhopal	.26	.22	17	.28	.24	15
Calcutta	.24	.23	05	.26	.24	06
Gopalpur	.24	.21	11	.21	.17	17
Nagpur	.25	.24	04	.24	.22	12
Bombay	.19	.20	—10	.26	.27	— 06
Mangalore	.04	.04	—07	.18	.18	—00
Jharsaguda	.24	.20	19	.26	.20	22
Allahabad	.25	.23	05	.18	.18	—08
Purnea	.24	.19	20	.16	.13	14
Ahmedabad	.27	.19	28	.25	.22	14
Jodhpur	.25	.22	12	.28	.17	03
Aurangabad	.23	.23	—01	.12	.13	—04

and n is the number of forecasts. The probability score shall be 0 if the forecasts are perfect and 1 if they are complete failures. Thus the lower probability scores go with more skillful forecasts. The probability scores (Murphy and Epstein 1967) for the forecasts based on

TABLE 2

Relative frequencies of rainfall occurrence for five classes of probability forecasts

Parameter	P_i				
	.1	.3	.5	.7	.9
Rainfall criteria $\geqslant 2.5$ mm					
Total No. of forecasts	122	209	226	199	156
Frequency of rainfall	26	78	128	138	138
Relative frequency of rainfall	.21	.37	.57	.69	.88
Rainfall criteria $\geqslant 10$ mm					
Total No. of forecasts	346	284	136	131	15
Frequency of rainfall	55	107	63	95	10
Relative frequency of rainfall	.16	.38	.46	.72	.66

climatic probability are also given in the same table. The skill-score in percentage are determined as

$$\text{Skill-score} = \frac{\text{PS (Climatology)} - \text{PS (Forecasts)}}{\text{PS (Climatology)}} \times 100$$

The skill-score of the forecasts are about 10% and are relatively higher for Jharsaguda, Purnea and Ahmedabad. However, the skill-scores are negative for Bombay, Mangalore and Aurangabad.

5.2. Reliability of forecasts

The forecasts are said to be reliable (Murphy and Epstein, *Loc. cit.*) if on verification, for all the cases for which a particular value of probability of rainfall (P_i) is forecast, the relative frequency (f_i) of occurrence of rainfall approximates the value P_i, i.e., $f_i \simeq P_i$. We have verified the relative frequency of occurrence of rainfall for five classes of P_i, with central values, .1, .3 .5, .7 and .9. After verification for individual stations, the verification sample (76) was found to be too small. Hence the relative frequencies of rainfall occurrence, corresponding to particular class of forecast probability are averaged over all the 12 stations and presented in Table 2.

The P_i and f_i match reasonably well except for the last class ($P_i = .9$) for the 10 mm case for which the the number of observations is too small. Thus, the forecasts produced by using the above composite charts are reliable and there is no overpredicting or underpredicting of the probability of rainy days.

6. Conclusion

The probability of occurrence of 24-hr rainfall $\geqslant$ 2.5 mm exceeds 0.8 over an area lying ahead of the depression and varying in extent from 3 to 5 deg. Lat. width and 5 to 10 deg. Long. in length, depending on the geographical position of the depression at the start of the 24-hr period. Likewise the probability of heavy rainfall exceeds 0.2 over an area about 2-3 deg. wide and 5-6 deg. long lying to the left of the depression track (Fig. 3b). The average rain exceeds 2 cm over

a rectangular belt 3-4 deg. wide and 7-10 deg. long lying to the left of the depression track (Fig. 3c). Reliable forecasts of rainfall point probabilities or expected areal coverage can be made, for the occasions when a depression is present over the Indian region, by using the above probabilities of rainfall associated with depressions. The skill score of the forecasts is expected to be about 10%.

This paper has dealt with statistics of rainfall in association with monsoon depressions. Distribution of rainfall has been explained on physical and dynamical considerations by many workers (e.g., Rajamani and Rao 1981) and hence no explanation has been put forward here.

References

Abbi, S.D.S., Gupta, D.K. and Hemraj, 1970, 'Forecasting heavy rainfall over Gujarat coast in association with Bay depressions moving westward', *Indian J. Met. Geophys.*, **21**, pp. 583-590.

Bedekar, V.C. and Banerjee, K.K., 1969, 'A study of climatological and other rainfall patterns over central India', *Indian J. Met. Geophys.*, **20**, pp. 23-30.

Chowdhary, A. and Gaikwad, S.D., 1983, 'On some characteristic features of rainfall associated with monsoon depression over India', *Mausam*, **34**, pp. 33-42.

Dhar, O.N. and Ghose, G.C., 1972, 'On some hydrometeorological aspects of space-time distribution of depressions and storms over major river basins in India', *Vayu Mandal*, **2**, pp. 125-131.

Dhar, O.N. and Mhaiskar, P.R., 1973, 'Areal and point distribution of rainfall associated with depressions/storms on the day of crossing the east coast of India', *Indian J. Met. Geophys.*, **24**, pp. 271-278.

India Meteorological Department, 1979, *Tracks of storms and depressions in the Bay of Bengal and the Arabian Sea*, 1877-1970, 186 pp.

Jorgensen, D.L., 1963, 'A computer derived synoptic climatology of precipitation from winter storms', *J. appl. Met.*, **2**, pp. 226-234.

Mooley, D.A., 1973, 'Some aspects of Indian monsoon depressions and the associated rainfall', *Mon. Weath. Rev.*, **101**, pp.271-280.

Mukherjee, A.K. and Shyamala, B., 1978, 'Distant effect of monsoon depressions on weather over west Rajasthan', *Indian J. Met. Geophys.*, **29**, pp. 47-53.

Murphy, A.H. and Epstein, E.S., 1967, 'Verification of probabilistic predictions—A brief review', *J. appl. Met.*, **6**, pp. 748-755.

Pisharoty, P. R. and Asnani, G.C., 1957, 'Rainfall around monsoon depressions over India,' *Indian J. Met. Geophys.*, **8**, pp.15-20.

Raghavan, K., 1967, 'Influence of tropical storms on monsoon rainfall in India,' *Weather*, **22**, pp. 250-256.

Rajamani, S. and Rao, K.V., 1981, 'On the occurrence of rainfall over southwest sector of monsoon depression, *Mausam*, **32**, pp. 215-220.