Synoptic Climatology of the Daily 700 mb Summer Monsoon Flow Patterns over India

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ABSTRACT

The daily (mean of 0000 and 1200 GMT) 700 mb contour patterns over India are classified in five broad types for each summer monsoon month by using a chart-to-chart correlation method. Certain characteristics of these patterns, such as mutual transitions, persistence, preferred periods of occurrence and interrelationships are studied. Statistical probabilities of two threshold 24 h rainfall amounts (2.5 and 10 mm) being equaled or exceeded for each type are computed for 107 stations, more or less uniformly distributed over India. This knowledge of the spatial distribution of precipitation probabilities associated with various circulation types can be used in forecasting probabilities of precipitation over the country if the circulation patterns can be forecast by numerical methods. These probabilities are then compared to the climatological and conditional probabilities of obtaining threshold rainfall amounts on different days of the subsequent 5-day period—given that the threshold rainfall occurred on the current day. The results, if averaged for all types and months, show that persistence is superior to the synoptic climatology developed in this study for forecasting precipitation probability for the next day over all regions and for forecasting precipitation probability up to 2–4 days—depending on region and threshold rainfall criteria. Synoptic climatology is superior to persistence as an aid for forecasting precipitation probability after 4 days over all the regions. Some shortcomings of the present study and future plans are described briefly.

1. Introduction

The summer monsoon season (June–September) contributes 50–90% of the annual rainfall over India except for two regions: 1) the area north of 32°N and 2) the extreme southeast peninsula. Forecasting the space and time distribution of monsoon rainfall is very important for India, whose economy depends on agriculture to a large extent. At present, forecasts of rainfall distribution over the various parts of the country for a 48 h period are issued by the India Meteorological Department in qualitative levels of confidence. These forecasts, issued for various meteorological subdivisions, are in terms of expected areal coverage or, more correctly, in terms of percentage of stations (of some fixed total number) expected to report more than 2.5 mm rain. The percentage does not have a continuous range from zero to 100 but the whole range is covered in four parts and the various phrases used are "widespread for 76–100% coverage, fairly widespread for 51–75%, scattered for 26–50% and isolated for 1–25%." The "no rain" areas are indicated separately. Local forecasts are issued in still more qualitative terms by using terms like one or two showers, a shower or two possible, intermittent rain at times heavy, etc., without any reference to amounts.

Given the circulation patterns at various levels, the forecaster issues a forecast based on his past experience of the behavior of different circulation systems, the rainfall distribution caused by them and qualitative use of certain theoretical concepts. It is worthwhile to add to this experience by some objective procedure. With this aim it is proposed to develop a synoptic climatology (SC) of the flow at the 700 mb level. The flow at 700 mb will be represented in this study by contour height distributions at selected grid points. This level was chosen for development of SC because experience of operational meteorologists has shown that the flow patterns at this level undergo orderly development and movement and the large-scale rainfall distribution over the country is well related to the systems observed at this level. Lal and RaiSircar (1960) found that during summer monsoon the circulation systems at 700 mb show more orderly development and better association with weather than the circulation systems at sea level. The SC is then developed by classifying the 700 mb level daily contour patterns in five broad types, separately for each monsoon month, and by computing for each type of patterns statistical probabilities of equalling or exceeding certain threshold rainfall amounts at 107 stations. Certain characteristics of these daily contour patterns, such as evolution, persistence, period of occurrence and interrelationships are also examined in order to see if a reasonable estimate about the circulation for the next few days can be made, given today's circulation. The SC presented in this paper can be used as an aid for the conventional synoptic forecasting procedures and to increase the range of the forecasts if the sequence of flow patterns at 700 mb can be forecast up to the desired range by

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some method. It may find a better application in the latter objective, i.e., of extending the range of conventional forecasting, if in the foreseeable future, flow patterns at an upper level like 700 mb are forecast 5–7 days in advance by numerical methods. Then the empirical relationships developed between the flow pattern and rainfall can be used to predict rainfall. Such a combination of dynamical and statistical weather prediction is known as the "perfect prog" method (Veigas, 1966) in meteorological literature. Finally, we shall compare the utility of this SC method in predicting rainfall over different parts of India against standards of climatology and persistence. No comparison with operational local forecasts is attempted, since these forecasts use qualitative phraseology. The conditional probabilities of certain rainfall thresholds occurring over the station on different days of the next 5-day period, given that the threshold rainfall is recorded today (zeroth day) at 0300 GMT (rainfall realized during the period from 0300 GMT of yesterday to 0300 GMT of today) are computed for all stations separately for each month. We shall also examine the period, up to which the persistence forecast will be superior (or inferior) to the forecast based on the SC developed, assuming that the 700 mb flow patterns on each day can be accurately forecast.

2. Data

The basic data are daily (mean of 0000 and 1200 GMT) gridpoint contour heights at 98 grid points (as shown in Fig. 1a) from manually analyzed charts. However, contour heights at only 30 points as shown in Fig. 1a have been utilized for the purpose of typing. This reduction of number of points was imposed by the limited memory of the computer (CDC 3600) used.

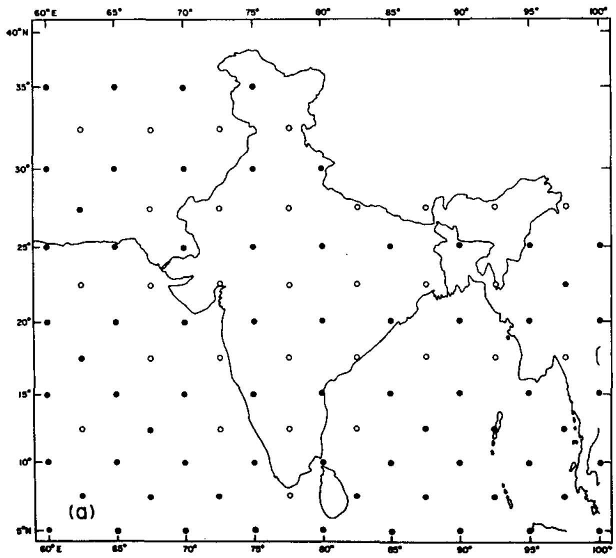


FIG. 1a. The 98 points of the basic grid (dots and circles). Circles also represent the 30 points considered in chart classification.

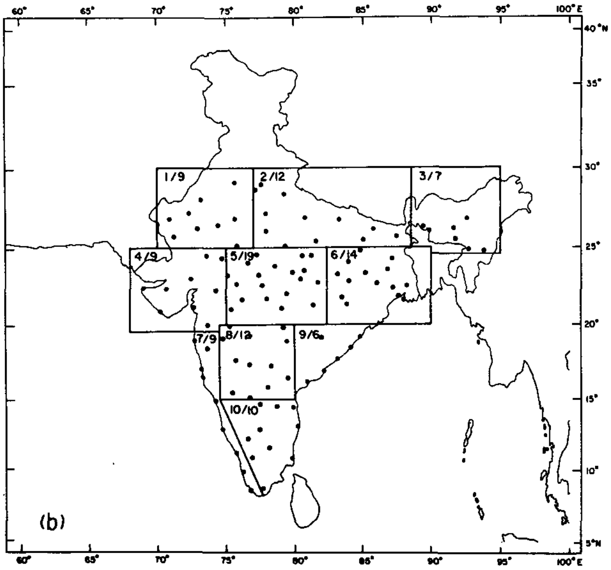


FIG. 1b. Locator map of rainfall stations. The serial number of the region followed by the number of stations in the region are given in top left corner of the regions.

However, we feel that since the neighboring grid points are highly correlated with each other, no information of value has been lost by reducing the number of grid points used for typing. These data, spanning the entire monsoon season (122 days from 31 May to 29 September), cover a period of 16 years from 1958 to 1973. The corresponding daily rainfall data of 107 stations (Fig. 1b) will range over a period of 122 days (1 June–30 September) corresponding to the conventional monsoon months. The lag of one day between the two data sets is considered because the rainfall associated with the circulation of a particular day is recorded at 0300 GMT of the next day. The averaging of the two synoptic hours removes diurnal variation and smoothes the flow field. This average flow is expected to be related to the 24 h rainfall measured at 0300 GMT the next day, rather than with the flow at an individual synoptic hour. Comparison with the daily wind field for several days with different types of synoptic situations revealed that the contour field is able to represent satisfactorily the major synoptic systems.

3. Normal contour patterns

The daily normal 700 mb contour patterns prepared from the data of 16 years are presented in Fig. 2 for selected days. The chief features on the normal chart of 1 June are a trough oriented north-south with its axis approximately along 90°E and a ridge dominating the central parts of the country, running from the central Arabian sea along about 20°N. The area of low contour values then gradually increases and by the end of first week of June the ridge disappears from

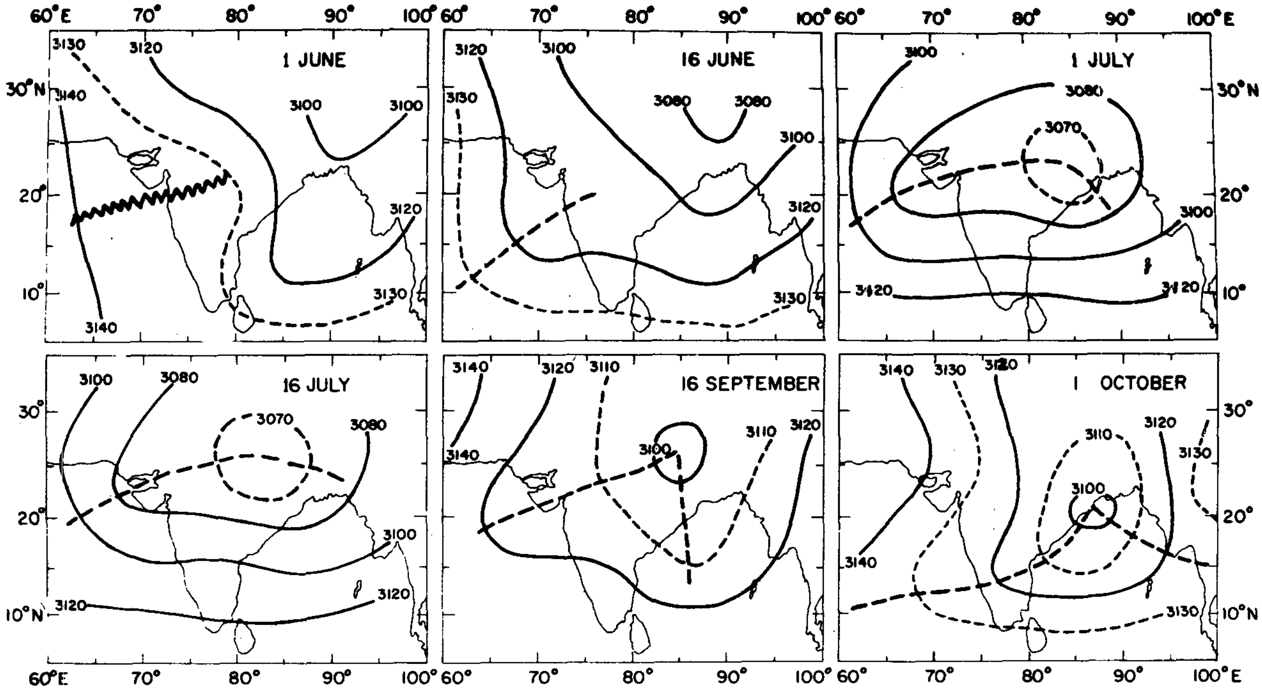


FIG. 2. Mean contour charts (based on 16 years of data) for selected dates showing all important changes in circulation patterns associated with the onset, established phase and withdrawal of the monsoon. Contour heights are in meters at intervals of 20 m (solid) and 10 m (dashed).

the country and by the end of second week of June a trough in the northeast Arabian sea appears which intensifies later. By 21 June the N–S trough at 90°E almost disappears and a trough running from northeast to southwest becomes distinct. This trough then starts accentuating and the eastward end of the trough gradually starts shifting southward so that by 27 June the trough attains almost east–west orientation with the axis running at approximately 20°N. Later, by about 1 July the trough moves to about 22.5°N and the monsoon is established over almost all the country. The trough axis continues to move northward and reaches 25°N by the end of first week of July. Thereafter, until the end of first week of September the trough oscillates around this position, changing its orientation at times. The area within the lowest contour line starts contracting rapidly from 13 September onward and the monsoon trough starts losing its E–W orientation so that by 16 September the lowest contour area is centered near 85°E, 25°N and two branches of trough run from this center, one in a N–S direction and the other in a NE–SW direction, resembling somewhat the pattern of 16 June. By 21 September a ridge appears over northwest India and the trough takes a curved shape, with the northern part running almost N–S along 85°E and the southern part NE–SW into the Arabian Sea. The lowest contour area shifts southward to 20°N by 1 October, and by the end of the first week of October the lowest contour area shifts further south to 12.5°N and the trough runs E–W along 12.5°N. By 15 October the monsoon normally withdraws from major parts of the country lying north of 18°N.

4. Method

a. *Chart classification*

The chart-to-chart correlation approach, similar to the one used by Lund (1963), Abe (1972), Paegle and Keirulff (1974) and Blasing (1975), has been used for the purpose of classification of contour charts. Only 15 years of data (1958–72) have been used for chart typing, thus providing 450 charts each in June and September and 465 charts each in July and August. While the rainfall refers to the dates of the calendar months the corresponding contour patterns considered pertain to the preceding dates.

The typing procedure followed separately for each month is given below:

1) Correlation coefficients between the first chart and all other charts for the month are computed and the charts with correlation coefficients equal to or above a prespecified threshold value are identified. The correlation vector V_{1j} is defined by

$$V_{1j}=\sum_{m=1}^{30} h_{1m}h_{jm}\Big/\Big(\sum_{m=1}^{30} h_{1m}^2 \sum_{m=1}^{30} h_{jm}^2\Big)^{\frac{1}{2}},$$

where j varies from 1 to 450 or 465 depending on the month and h_{1j}, h_{jm} represent the deviations of the contour height at grid-point m from chart averages for the 1st and jth charts, respectively.

2) By repeating the procedure in 1) for all the charts in a month, the number of the correlation coefficients which are equal to or exceed the threshold value in the respective correlation vectors, V_{1j}, V_{2j}, ..., V_{ij}, etc., are counted.

3) The chart having the maximum number of correlation coefficients exceeding the threshold value is classified as A type. The correlation coefficients between this typical chart and all other charts of the month are recomputed to locate the charts which have correlation coefficients equal to or greater than the threshold value with the A type. All these correlated charts are removed from the list of charts, since they are likely to belong to group A as they are highly correlated with the typical A chart.

4) Procedures 1)–3) are repeated on the remaining charts and the next type (B) is identified. The computerized procedure of typifying the charts was continued until the last type did not include even 10 charts, and in this way in most of the months 9 or 10 types were recognized. However, only first five types were retained since other types did not contain sufficient number of charts to enable the development of synoptic climatology with reasonable confidence.

5) For each chart, correlation coefficients with all the typical charts are examined, and the chart under consideration is assigned the type with which it has maximum correlation coefficient.

While following the above procedure, certain subjective criteria have been adopted. A chart has been classified into a type only if it has at least a correlation coefficient of 0.7 with any of the typical charts. This value is much higher than the significant correlation of 0.45 at the 1% level for a sample size of 30. This is because there is a high amount of spurious (seasonal) correlation due to the seasonal latitudinal gradient of contour heights, which accounts for about 0.5 of the correlation coefficient between the charts (Brooks and Carruthers, 1953). Since the amount of this seasonal correlation in transition months differs from that in the months of the established monsoon, different values of the threshold correlation coefficient have been used. However, in a relatively few cases when a particular chart does not have correlation coefficient of even 0.7 with any typical chart but has a correlation coefficient of more than 0.5 with any one of the typical charts, and a very low correlation coefficient with other typical charts, the chart is classified into the type with which it has a correlation coefficient of more than 0.5. This is necessary to raise the number of charts in those types which would otherwise have less than 20 charts, a value too small to permit computation of the necessary statistics based on sufficient number of charts. Knowles and Jehn (1975) noted that for a 5%

TABLE 1. The typing information. The figures below the month represent the total number of charts in the month.

Month	Threshold correlation	Type	Date of type	Number of charts selected
June	0.7	A	12 June 1962	141
(450)		B	6 June 1969	89
		C	26 June 1964	14
		D	12 June 1966	49
		E	3 June 1964	53
		M	—	104
July	0.8	A	9 July 1961	167
(465)		B	4 July 1961	84
		C	7 July 1961	107
		D	6 July 1963	46
		E	23 July 1966	15
		M	—	46
August	0.8	A	8 August 1971	157
(465)		B	2 August 1965	91
		C	11 August 1964	49
		D	7 August 1962	27
		E	31 July 1963	54
		M	—	87
September	0.7	A	1 September 1967	111
(450)		B	26 September 1963	51
		C	31 August 1960	67
		D	8 September 1969	42
		E	22 September 1960	37
		M	—	142

error of computation in precipitation probabilities the minimum sample size required is 20. In this study we obtained more than 20 charts of each type except for C type in June and E type in July (Table 1). Although more general types could be prepared by combining these rare types with other types, it was not thought desirable to prepare such general types at the cose of a decrease in the stratification of precipitation frequencies. If a chart has equal correlation coefficients with two typical charts then the chart is classified into the previous or the following type keeping persistence in view. However, such cases are few. After considering the five types, about 10–30% of the charts remained unclassified and these have been called charts of mixed type, symbolized by M.

The threshold correlation coefficient has been decided on a trial basis and is different for transition months and months of established monsoon. It is found that the use of higher thresholds results in the inclusion of few cases in each type, greater similarity between types, and a greater number of the charts not being included in any type, whereas the use of lower thresholds includes too many charts in the first few types and sufficiently distinct flow types cannot be classified. We have compromised between these two extremes so that about one-third of the charts come in the first dominant type and sufficient charts are included in the other types.

DATE	1958	1959	1960	1961	1962	1963	1964	1965	1966	1967	1968	1969	1970	1971	1972
31 MAY	E	A	A	A	E	M	E	A	E	E	E	A	C	M	E
1 JUNE	E	A	M	A	E	A	E	A	M	E	E	B	M	B	E
2 "	E	A	M	E	A	B	E	A	M	E	E	B	B	B	E
3 "	E	A	E	M	M	B	E*	A	M	E	E	B	B	B	E
4 "	A	A	A	M	M	B	E	D	M	E	E	B	B	B	E
5 "	E	A	A	A	M	M	E	D	M	A	E	B	A	B	E
6 "	E	B	M	A	B*	M	E	D	M	A	B	B	A	B	E
7 "	E	A	M	A	B	M	A	A	M	A	B	B	B	B	E
8 "	A	A	M	B	A	B	M	A	M	A	A	A	B	B	E
9 "	A	B	M	B	A	B	M	A	M	M	A	A	M	A	E
10 "	E	B	M	M	A	C	M	E	M	M	A	D	M	A	E
11 "	E	B	A	B	A	A	M	A	M	M	E	D	M	D	A
12 "	E	A	A	A	A*	A	M	A	D*	M	B	D	M	D	A
13 "	A	A	D	A	A	A	M	A	D	M	B	A	M	D	E
14 "	E	A	D	A	B	A	E	A	D	M	M	D	M	D	B
15 "	A	E	D	A	A	A	A	A	D	M	B	D	M	B	E
16 "	M	M	D	A	A	A	A	A	B	D	C	D	M	B	E
17 "	B	M	D	A	B	A	A	A	A	D	A	A	D	B	A
18 "	A	M	A	M	B	A	B	A	D	D	A	A	B	B	A
19 "	A	M	A	M	B	A	B	A	D	M	A	B	B	B	B
20 "	A	M	B	M	D	D	M	B	D	M	A	A	B	B	C
21 "	D	M	B	M	A	D	C	B	D	M	A	D	B	M	A
22 "	A	M	M	M	B	E	C	A	D	B	D	D	A	M	A
23 "	B	M	M	M	A	A	B	A	D	M	A	A	B	M	A
24 "	M	M	B	M	D	M	C	D	D	M	A	A	B	B	A
25 "	A	M	M	M	A	M	C	A	A	M	B	B	B	D	A
26 "	B	M	M	M	A	M	C*	A	A	C	B	B	M	D	A
27 "	M	M	C	M	A	M	C	A	A	M	A	B	C	D	A
28 "	M	B	B	B	A	M	B	A	D	M	A	B	M	D	A
29 "	B	M	B	D	A	A	B	A	A	C	B	B	M	D	M

DATE	1958	1959	1960	1961	1962	1963	1964	1965	1966	1967	1968	1969	1970	1971	1972
30 JUNE	B	B	B	A	A	A	D	A	A	B	M	D	D	D	B
1 JULY	B	B	B	B	A	D	A	A	C	C	M	A	E	E	B
2 "	B	C	B	B	M	D	B	C	C	B	D	D	C	C	B
3 "	M	C	B	B	M	D	B	C	C	B	D	D	C	C	C
4 "	M	E	B	B*	M	D	A	B	A	C	D	A	A	A	A
5 "	M	B	C	B	B	D	D	C	A	C	B	D	A	A	A
6 "	M	C	C	C	D	D*	C	A	A	C	A	A	A	A	C
7 "	M	C	A	C*	B	D	C	A	A	C	C	A	A	A	B
8 "	A	A	C	A	B	B	C	A	M	A	C	A	D	D	C
9 "	A	A	C	A*	B	A	A	C	M	A	C	A	B	B	B
10 "	B	A	C	A	B	A	A	A	M	C	A	A	A	A	A
11 "	B	D	C	A	B	A	C	A	M	C	C	A	A	A	A
12 "	C	D	A	A	B	A	C	A	M	A	C	D	A	A	A
13 "	A	B	A	A	B	A	C	D	C	M	C	B	A	A	A
14 "	A	B	A	A	B	A	C	D	C	M	A	B	A	A	A
15 "	A	M	M	A	E	A	C	B	A	M	A	B	C	C	D
16 "	A	E	M	D	B	A	C	B	C	C	A	A	C	C	A
17 "	C	M	M	A	C	A	A	C	B	C	C	A	C	C	A
18 "	A	E	M	B	C	A	C	A	B	M	B	C	A	A	A
19 "	A	A	M	B	C	A	A	B	B	M	B	A	A	A	A
20 "	A	A	M	B	A	A	D	B	B	M	M	A	C	C	A
21 "	A	B	M	B	A	C	D	B	M	M	C	B	C	C	A
22 "	A	B	M	B	D	A	D	C	E*	A	A	B	C	C	A
23 "	A	B	M	B	A	A	D	A	E	E	C	E	C	C	A
24 "	A	B	D	B	A	D	M	A	A	C	A	E	A	A	A
25 "	A	B	D	B	A	D	B	A	E	C	M	C	A	A	A
26 "	A	A	B	B	A	D	M	A	C	E	M	C	C	C	A
27 "	A	C	D	M	A	B	M	B	A	E	M	C	C	C	A
28 "	A	C	D	M	A	D	M	D	C	B	A	E	C	C	A
29 "	A	C	D	A	D	B	M	A	A	C	B	A	A	A	A
30 "	C	C	C	C	D	D	B	B	C	B	C	C	C	C	C

DATE	1958	1959	1960	1961	1962	1963	1964	1965	1966	1967	1968	1969	1970	1971	1972
31 JULY	A	A	C	B	D	E*	M	B	A	M	E	A	A	B	B
1 AUG	A	B	A	B	M	E	M	B	E	M	B	A	A	B	M
2 "	A	B	A	B	B	B	B	B*	E	M	B	A	A	B	M
3 "	E	B	C	A	A	A	C	B	A	A	A	A	E	A	M
4 "	M	A	C	B	A	D	D	B	B	A	A	A	E	A	D
5 "	B	A	C	A	A	M	C	B	B	B	E	A	A	B	A
6 "	B	A	A	A	D	C	M	B	A	B	E	B	A	A	C
7 "	E	A	D	A	D*	A	M	B	E	B	M	A	E	A	D
8 "	M	A	C	A	M	A	C	B	E	B	B	A	E	A*	C
9 "	M	A	C	E	M	A	C	B	E	B	B	A	E	A	A
10 "	M	A	A	A	C	A	C	M	B	B	B	A	C	E	A
11 "	M	A	A	B	C	A	C*	M	B	A	B	A	M	E	A
12 "	B	D	A	A	C	E	E	M	B	A	A	A	M	A	A
13 "	A	C	A	D	C	E	E	M	B	A	A	A	M	E	A
14 "	B	E	A	C	C	A	B	M	A	B	A	M	C	A	A
15 "	A	E	A	E	C	A	A	M	A	B	A	E	M	A	C
16 "	A	B	A	M	E	C	A	M	M	A	A	E	M	E	A
17 "	D	B	C	M	E	C	B	M	M	A	A	E	D	E	E
18 "	C	A	E	A	E	C	A	M	A	B	A	B	M	B	E
19 "	C	A	A	A	B	C	E	M	B	A	A	B	M	M	E
20 "	D	M	A	A	B	C	A	D	A	A	B	B	M	M	D
21 "	M	C	A	A	B	A	A	M	A	M	B	B	M	M	A
22 "	M	M	A	M	B	B	B	M	B	M	B	M	M	M	A
23 "	M	C	A	M	A	B	A	C	B	A	A	M	A	M	A
24 "	M	C	A	D	D	A	A	E	B	A	B	M	B	M	A
25 "	E	D	A	C	D	D	A	E	B	E	B	M	M	M	A
26 "	A	M	E	C	M	D	C	E	B	B	B	M	A	D	A
27 "	A	C	E	M	E	C	E	B	B	M	B	M	A	M	A
28 "	A	C	A	M	E	C	M	B	B	A	B	M	E	C	A
29 "	M	D	A	D	M	E	D	B	B	A	B	M	E	C	A
30 "	D	D	A	A	M	C	M	A	M	A	M	M	A	C	A

DATE	1958	1959	1960	1961	1962	1963	1964	1965	1966	1967	1968	1969	1970	1971	1972
31 AUG	D	D	C*	A	M	A	M	M	C	A	M	M	A	A	A
1 SEP	M	A	C	A	B	A	M	D	M	A*	M	M	A	A	A
2 "	M	D	C	A	B	A	C	A	A	A	M	M	A	A	C
3 "	C	A	C	A	B	A	A	A	A	A	M	D	A	A	C
4 "	C	M	B	A	A	A	C	B	D	A	M	D	M	A	C
5 "	C	M	B	M	A	D	C	A	D	A	M	D	A	A	C
6 "	A	M	B	M	M	A	A	A	M	M	M	D	M	A	B
7 "	A	M	B	M	E	A	A	A	M	M	M	D	M	A	B
8 "	A	A	D	D	E	A	A	C	C	M	B	D*	M	A	B
9 "	D	A	D	M	D	A	A	C	C	C	M	M	M	C	B
10 "	D	A	D	M	M	A	M	C	C	C	M	M	M	C	D
11 "	M	M	M	A	M	M	M	C	C	A	B	A	M	C	D
12 "	M	A	M	M	M	A	E	C	C	A	B	A	M	C	A
13 "	M	D	C	A	A	A	E	B	C	M	D	A	C	C	M
14 "	M	A	C	A	M	A	E	B	C	M	A	A	C	M	M
15 "	C	M	C	A	A	A	E	B	M	A	A	A	C	B	M
16 "	C	C	A	A	B	C	E	M	M	A	A	D	C	M	B
17 "	C	M	E	A	D	C	E	M	C	C	M	D	C	M	M
18 "	C	C	E	A	D	C	M	M	C	C	M	B	C	M	M
19 "	C	A	E	C	A	A	M	M	M	M	M	D	C	E	M
20 "	M	C	E	C	M	A	A	M	M	M	M	D	M	E	M
21 "	M	C	E	M	M	M	C	M	M	M	M	A	D	E	M
22 "	D	B	E*	D	C	B	B	M	M	B	M	A	D	E	B
23 "	D	E	E	D	C	E	A	M	M	E	M	A	M	E	M
24 "	D	E	B	D	C	B	A	B	B	E	M	A	M	E	M
25 "	M	E	B	A	A	B	M	B	B	M	M	A	M	E	M
26 "	M	E	D	A	M	B*	M	B	E	M	M	C	M	E	M
27 "	A	B	M	A	M	B	D	B	E	M	M	B	A	D	M
28 "	A	B	M	A	M	B	E	B	E	M	M	B	A	D	M
29 "	A	B	B	B	M	B	E	B	E	M	E	B	M	A	M

FIG. 3. Chart type assigned to each day. The charts marked by asterisks are the typical charts (see text).

b. Characteristics of chart types

From the sequence of contour pattern types as shown in Fig. 3, we have computed the frequencies of the occurrence of each type in different 10-day periods, the frequencies of all possible pattern transitions (Table 2) and frequencies of spells of various lengths for each type (Table 3), for all months separately. These data will be discussed in appropriate sections below.

c. Development of synoptic climatology

We have computed probabilities of 24 h rainfall of 2.5 mm or more [the conventional definition of a rainy day adopted by the India Meteorological Department

TABLE 2. Frequencies of different transitions. The values expected by chance (in parentheses) are rounded to the nearest integer.

Month	Chart type	A	B	C	D	E
June	A	87 (55)	16 (30)	3 (4)	12 (20)	13 (21)
$\chi^2=328.73$	B	20 (32)	47 (18)	3 (2)	3 (11)	3 (12)
	C	0 (3)	4 (2)	4 (0)	0 (1)	0 (1)
	D	13 (19)	3 (11)	0 (1)	30 (7)	0 (8)
	E	8 (18)	1 (10)	0 (1)	1 (7)	34 (7)
July	A	103 (65)	8 (31)	36 (39)	8 (17)	3 (6)
$\chi^2=233.41$	B	10 (32)	46 (15)	7 (19)	11 (8)	3 (3)
	C	31 (43)	15 (20)	51 (26)	2 (11)	5 (4)
	D	16 (17)	5 (8)	0 (10)	19 (4)	0 (1)
	E	2 (5)	2 (2)	3 (3)	2 (1)	3 (1)
August	A	97 (63)	27 (36)	7 (18)	3 (7)	11 (21)
$\chi^2=288.24$	B	18 (36)	54 (20)	0 (10)	0 (4)	10 (12)
	C	6 (17)	1 (10)	22 (5)	8 (2)	2 (6)
	D	8 (8)	0 (4)	5 (2)	4 (1)	1 (3)
	E	16 (21)	1 (12)	8 (6)	0 (2)	24 (7)
September	A	69 (32)	3 (14)	8 (21)	11 (12)	0 (12)
$\chi^2=465.19$	B	3 (14)	27 (6)	6 (9)	1 (5)	3 (5)
	C	10 (19)	0 (9)	44 (12)	0 (7)	0 (7)
	D	6 (12)	6 (5)	0 (8)	19 (4)	2 (4)
	E	1 (12)	4 (5)	0 (8)	1 (4)	27 (4)

(IMD)] and 10.0 mm or more (since the average rainfall on central plains is about 10 mm day^{-1} during the established monsoon period) for 107 stations, associated with each type of pattern, for all months. These probabilities will hereafter be referred to as type probabilities and shall be symbolized by P_T (Fig. 4). We have also computed the climatic probabilities of 24 h rain of 2.5 mm or more and 10 mm or more for the same 107 stations and for all the monsoon months (not presented). The patterns of these probabilities are in close agreement with the patterns of the number of rainy days computed on the basis of longer records (India Meteorological Dept., 1971), but we shall be using probabilities based on 15 years' data as climatic probabilities. We have also computed for all months and all stations the conditional probabilities of different days in the next 5-day period receiving rainfall of 2.5 mm or more and 10.0 mm or more if the current day received more than 2.5 mm and 10.0 mm of rainfall, respectively. These probabilities, which bring out the influence of persistence in affecting rainfall expectation on different days, shall be symbolized by P_{wi}, where i varies from 1 to 5, depending on the number of days after the day on which threshold rainfall has been recorded. These climatic probabilities and conditional probabilities shall be used as standards for comparison of the utility of the synoptic climatology developed.

5. Results and discussion

a. *Discussion of chart characteristics*

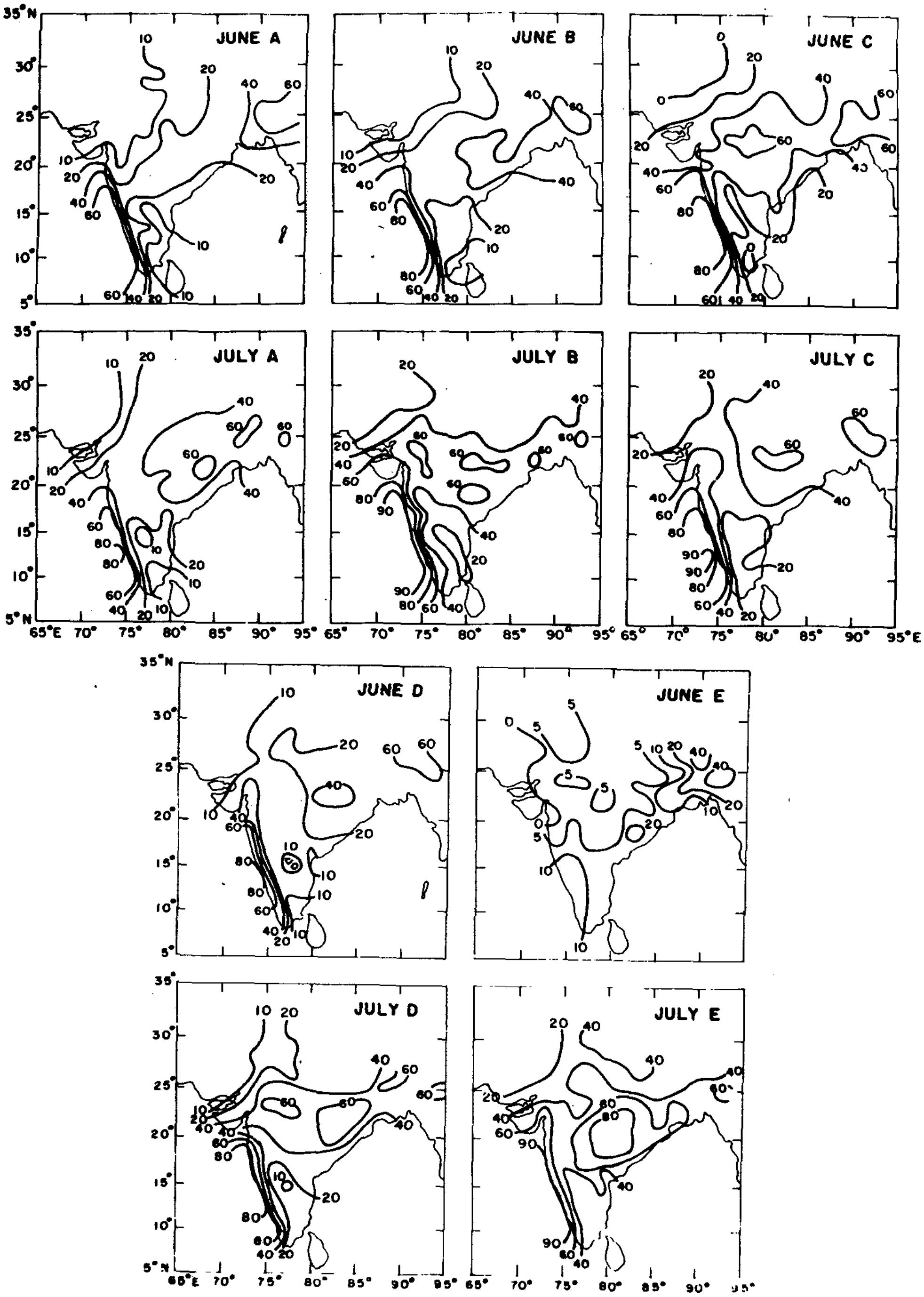
The five typical patterns classified for each month are given in Fig. 5. All 98 points of basic grid have been used for drawing these figures. The classification brings out the following typical patterns: 1) At the beginning of June, the E type is similar to the normal chart of 1 June with a ridge running across the country along 17°N up to 85°E and a trough lying over NE India with its axis along 95°E. Though the trough over NE India is not as obvious on the typical chart of 3 June 1964, as compared to that on the normal chart of 1 June, it is still retained since this was the chart type found by the objective procedure envisaged above. This may perhaps be due to the averaging of the synoptic charts, corresponding to two synoptic hours. However, the ridge at about 16°N which is a feature of late May or early June, is quite distinct.

2) By the end of June, the C type is similar to the normal chart of 1 July with the monsoon trough being established almost E–W over the country running along approximately 20°N latitude, and the intermediate types (A, B, D) have developed during the gradual advancement of the monsoon over the whole country.

3) In July the charts differ from each other mainly due to different positions and orientations of the monsoon trough axis. The axis is more or less E–W over the central longitudes of the country, it is displaced southward for the B type (22.5°N) which resembles the normal chart of 1 July, lies along 20°N for the D type and is displaced northward for the C type (27.5°N). In the A type the monsoon trough, although not E–W, is relatively northward with a low centered at 27°N, 82.5°E and in the E type, which is relatively rare, there are two lows, one in the Bay of Bengal and the other at 26°N, 70°E with the trough axis running NW–SE passing through 22.5°N, 78°E.

TABLE 3. Observed frequencies in count of spells of various length (days) for all the five contour patterns in each month.

Month	Length of spell	A	B	C	D	E
June	1	20	20	8	8	10
	2	16	12	1	2	2
	3	7	5	0	4	2
	4	2	1	1	2	1
	5	3	1	0	2	1
July	1	30	21	29	16	9
	2	15	8	11	5	3
	3	4	4	10	3	0
	4	6	1	5	1	0
	5	2	3	0	0	0
August	1	23	19	16	20	13
	2	17	5	6	3	11
	3	8	5	2	0	6
	4	3	4	1	0	0
	5	1	0	1	0	0
September	1	16	13	6	13	2
	2	9	3	6	6	3
	3	5	4	4	3	0
	4	4	2	2	0	2
	5	5	0	3	0	0



4) In August, like July, the patterns again differ mainly due to location and orientation of the monsoon trough. The monsoon trough is relatively southward for C (21°N) and D (19°N) types and at about the same position as on normal charts for August for the B and E types (25°N). In the A type, the trough axis is tilted NW–SE and located at about the same latitudes as on normal charts for the month.

5) In September, the almost E–W monsoon trough axis is seen in the A (23°N) and D types (22°N), representing early September, while the monsoon trough axis has shifted much to the south in the B (18°N) and E (14°N) types and resembles the normal chart of 1 October, in which a ridge from west Pakistan extends to 77°E representing withdrawal of monsoon from the central parts of the country. In the C type, the monsoon trough has a NE–SW orientation representing an intermediate phase of monsoon withdrawal, resembling the normal chart of 16 September. The D type resembles the normal chart of 1 September but

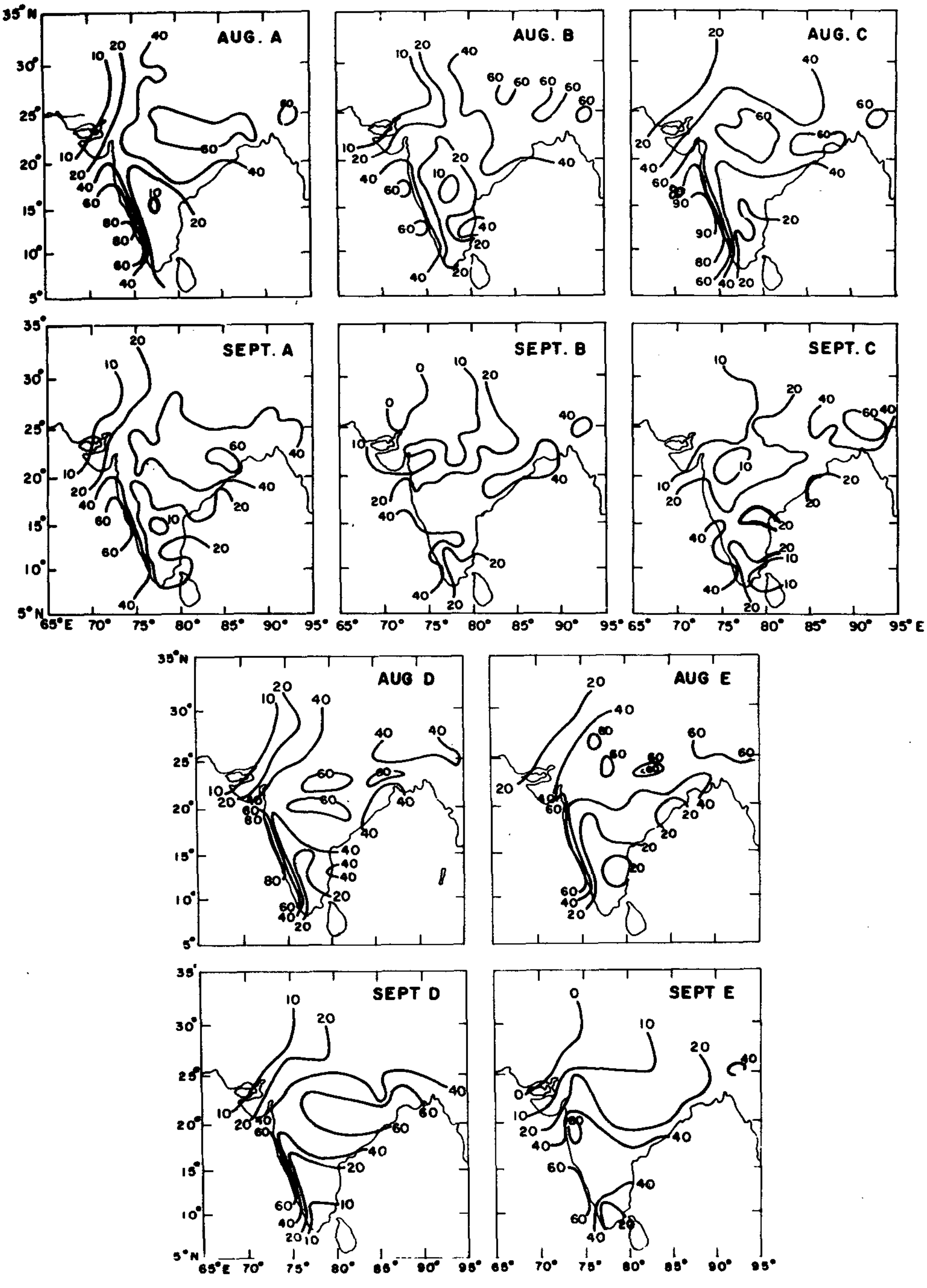
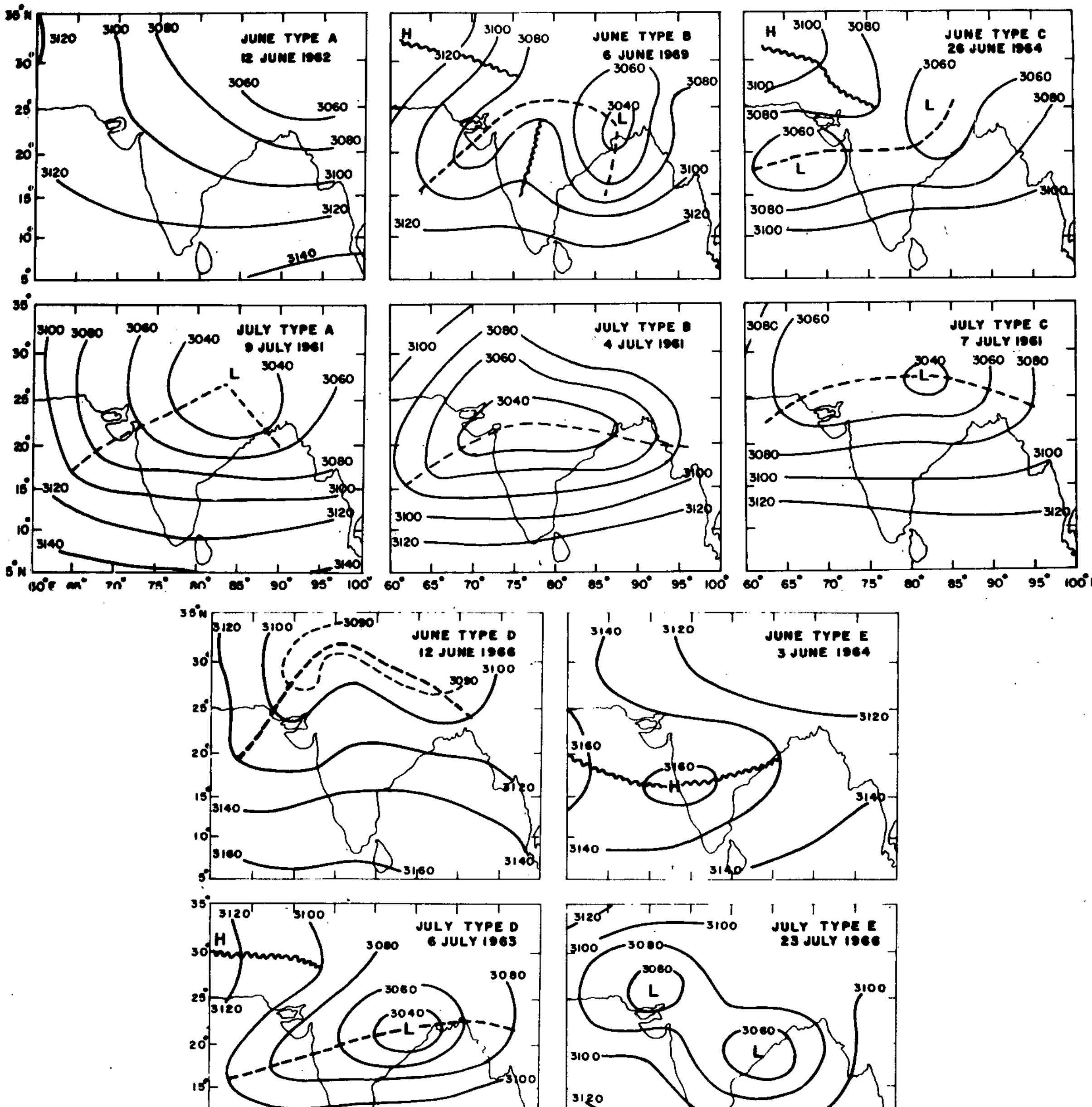


FIG. 4. Probabilities (percent) of 2.5 mm or more 24 h rainfall associated with each type of contour patterns. The isopleths are drawn for 0, 10, 20, 40, 60, 80 and 90% probabilities. For type E in June the 5% isopleth is also included for better representation.

with a trough position further southward by about 5° latitude.

We have discussed here only typical charts. The features on individual charts may differ in minor details from those on typical charts.

The frequency distribution of different types of charts during three 10-day periods of each month (not presented but can be inferred from Fig. 3) shows that during July and August there is no clearcut preference period for the occurrence of these charts except for the B type in August which shows a slight preference to occur in the first 10-day period of August. But in the transition months of June and September, preference in the period of occurrence is shown by some type of chart and this preference of period is strongly



controlled by the regular climatological evolution of patterns related with the onset or withdrawal of the monsoon over the country. For a detailed sequence of chart evolution the reader may refer to Fig. 3.

b. Type transitions

We have examined the transition of all the types of charts in a month into all other types of charts in the month to see if there is any regular evolution from one type to another. Frequencies of these transitions are given in Table 2. Frequencies expected on the basis of chance for each transition are given in parentheses. A particular transition is preferred (inhibited) for which the frequency of occurrence is more (less) than that expected by chance. The chi-squared (χ^2) statistic computed for each month separately is found to be significant at the 0.1% level, indicating nonrandomness of transitions. Since the degrees of freedom are 16 for each month, the χ^2 statistics are quite reliable even though many transitions show expected frequencies < 5 (Maxwell, 1964). A minimum expected cell frequency of 1 is assumed where it is found to be less than 1 in these computations. However, such occasions

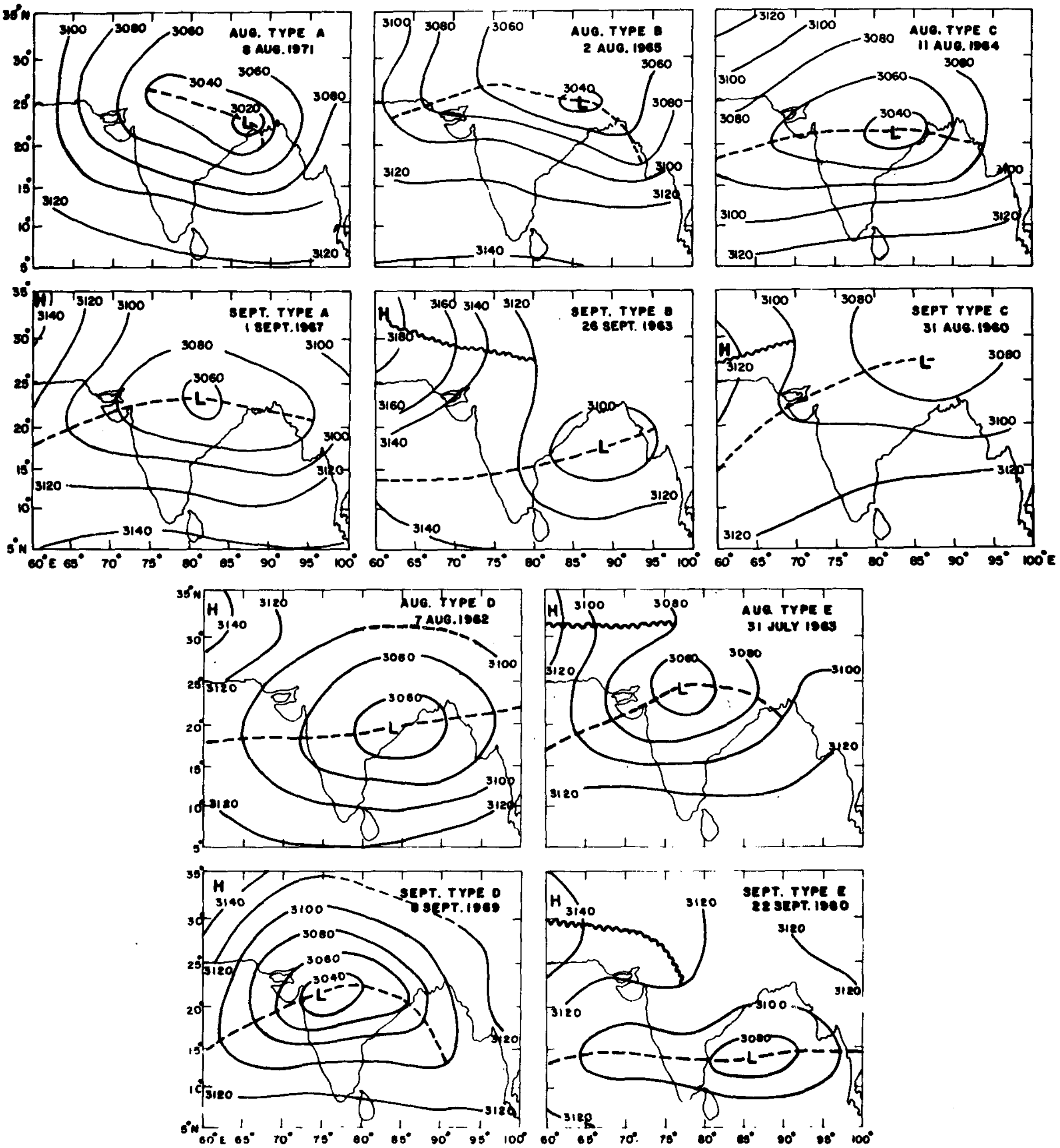


FIG. 5. Typical 700 mb charts obtained through the objective procedure. Contour heights are in meters drawn at intervals of 20 m except for June type D when a 10 m interval is used. Troughs and ridges are marked by dashed and wavy lines, respectively. Lows (L) and highs (H) are also indicated.

occur only once in June, July and August. The combined contribution toward χ^2 statistics by the five diagonal elements of the contingency tables is about 75% of the total. Thus we find that in all months a pattern type is more often followed by itself than any other type. There is no clearcut preference of inter-type transitions. In transition months, the observed frequency is comparatively much less than that expected by chance for certain transitions from the C, D and E types, indicating inhibited transitions. Other transitions are totally prohibited although the expected frequency on chance is not zero as can be seen from Table 2. With the help of Table 2 and a knowledge of the preferred periods of occurrence mentioned above, we can write the sequence of evolution of charts in the transition months as

June $E \rightarrow A/B \rightarrow D/A \rightarrow C$.

September $A/D \rightarrow C/A \rightarrow A/B \rightarrow E$.

The symbolism indicates that June most often begins

TABLE 4a. Intercorrelation coefficients between different types.

Month	Chart type	Chart type A	B	C	D	E
June	A	1.00	0.75	0.51	0.71	0.79
	B	0.75	1.00	0.80	0.46	0.41
	C	0.51	0.80	1.00	0.32	0.05
	D	0.71	0.46	0.32	1.00	0.57
	E	0.79	0.41	0.05	0.57	1.00
July	A	1.00	0.60	0.80	0.74	0.46
	B	0.60	1.00	0.48	0.78	0.67
	C	0.80	0.48	1.00	0.36	0.45
	D	0.74	0.78	0.36	1.00	0.44
	E	0.46	0.67	0.45	0.44	1.00
August	A	1.00	0.78	0.80	0.63	0.76
	B	0.78	1.00	0.38	0.13	0.60
	C	0.80	0.38	1.00	0.76	0.73
	D	0.63	0.13	0.76	1.00	0.30
	E	0.76	0.60	0.73	0.30	1.00
September	A	1.00	0.51	0.69	0.50	−0.03
	B	0.51	1.00	0.21	0.53	0.70
	C	0.69	0.21	1.00	−0.09	−0.43
	D	0.50	0.53	−0.09	1.00	0.54
	E	−0.03	0.70	−0.43	0.54	1.00

with the E type which evolves commonly into the A or B type which in turn is changed to the D or A type and, finally evolves into the C type when the monsoon holds sway over most of the country. The reverse sequence in September is such that the A or D types evolve into C or A types, which in turn evolve into A or B types, and finally into the E type when the monsoon trough recedes much to the south heralding the withdrawal of monsoon from northern and central plains. It may be recalled here that the A, B, etc., types of June and September are not similar.

c. *Interrelationship between flow types*

There is a high intercorrelation between all charts, particularly in the months of the established monsoon, because of the seasonal correlation. Hence even the typical charts in a month have significant correlation coefficients among themselves. These intercorrelation coefficients are given in Table 4a. The intercorrelation coefficients in September are at times negative because in this month the region of lower contour heights shifts for some types of south of 20°N, reversing the general contour height distribution. In other months these correlation coefficients are positive for all types. This interrelationship is useful in studying the evolution of charts, particularly in the transition months where evolution is gradual. A chart is more likely to evolve into a type to which it has maximum correlation.

The grid-point contour heights were tested for significance of the difference between means by applying the t-test, for all possible combinations of pairs of patterns, in the individual months. The number of points (out of 30) showing significant mean differences at the 1% level of significance are shown in Table 4b. On an average about 70% of the grid points show significant differences. If the individual charts in each type are identical to each other then we can expect more (less) grid points showing significant differences in means if the intercorrelation coefficients between the typical charts are lower (higher). This relationship between the intercorrelation coefficients and the number of points showing a significant difference of means is not clearly shown by Tables 4a and 4b, indicating thereby that all individual charts included in a type are not identical to each other.

d. *Persistence of flow patterns*

We have already seen above in Section 5b that the most preferred transition is to itself, i.e., the flow persists. We shall look further into this persistence of flow. For this we have computed the frequency distribution of spells of different length for each flow type from Fig. 3.

However, the spells of length longer than 5 days (not shown) are very few, meaning that a particular type of pattern rarely persists beyond 5 days. The frequency of spells of longer than 2 days falls rapidly. A cursory subjective examination revealed that flow types in a weak monsoon period are comparatively more persistent than in an active monsoon period. This is because formation, movement and dissipation of synoptic systems can change the type in a relatively shorter period.

e. *Synoptic climatology*

We have computed precipitation probabilities associated with each type for both threshold criteria. How-

TABLE 4b. Number of grid points at which the mean contour height difference is significant at the 1% level for different pairs of types.

	June A	B	C	D	E	July A	B	C	D	E	August A	B	C	D	E	September A	B	C	D	E
A																				
B	21					25					24					22				
C	17	9				21	28				25	25				24	21			
D	17	22	18			22	17	28			18	24	9			18	21	23		
E	28	26	21	26		17	10	17	13		16	23	18	19		25	15	27	23	

ever, since the results are more or less similar, the discussion will be primarily confined to the 2.5 mm criterion in what follows below. We find (Fig. 4) that although stratification of types into a range of precipitation probabilities has been achieved, it is not to the extent hoped for. The ideal stratification means that either the precipitation probability is zero or 100% for a station, corresponding to a particular flow type. We see, however, that over the central parts of the country (say around 20°N, 77°E) the probability varies from 5 (E type) to 60% (C type) in June, 50 (A, C types) to 80% (E type) in July, 40 (B type) to 60% (A, C, D, E types) in August and 20 (B, C types) to 60% (D type) in September. Near 0% probability in the west Rajasthan (region 1) and Tamilnadu (region 10) areas and near 100% probability in the western ghats (region 7) in association with some types are due to the fact that these are the extreme dry and extreme wet regions, respectively. Moreover, over the west coast, orography plays a dominant role in causing precipitation and plays an enhanced role in augmenting precipitation when synoptic factors are favorable. It rains (rainfall $\geqslant$2.5 mm) on 20–25 days in June, July and August and 15–20 days in September along the west coast. In Assam (region 3), the other hilly region, the frequency of rainy days is somewhat less.

The different types of flow do show different distributions of precipitation probability which can be better recognized if we plot the difference of climatic and type probabilities on charts. We find (See Fig. 6) that the areas covered by either higher or lower type precipitation probabilities than the climatic probabilities are large in size, indicating the effectiveness of flow patterns in changing large-scale precipitation probability patterns over the country. The areas of low (high) contour heights for all types are associated with high (low) precipitation probability in comparison to climatic probability. The difference between the type and the climatic probabilities of rainfall over the central parts of the country ranges from 10–40% in June and July, 10–20% in August and 15–40% in September.

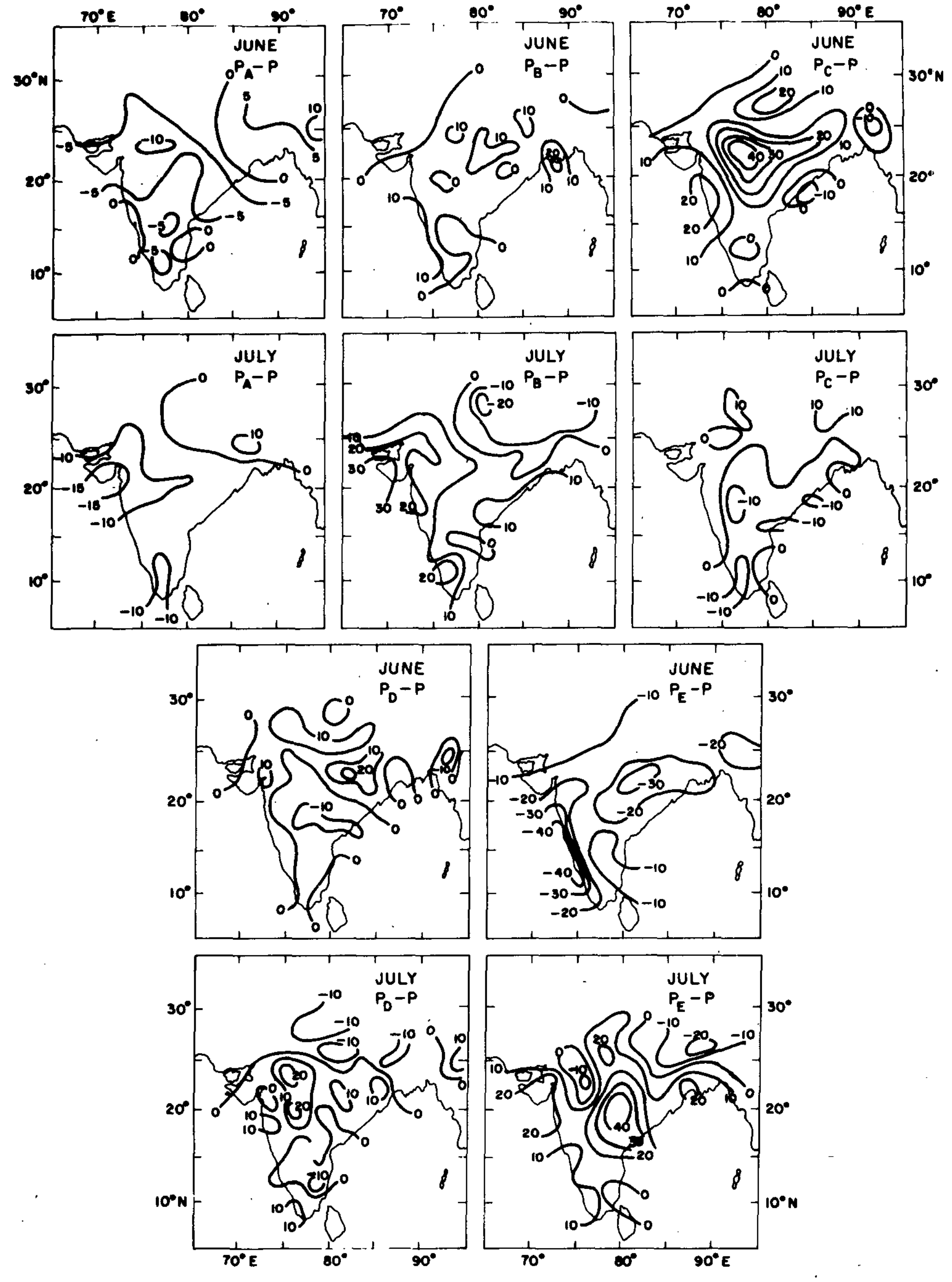
6. Application of the synoptic climatology in forecasting

The probability statement of precipitation can be given different meanings (Murphy and Winkler, 1971). In this study, by probability of certain threshold precipitation (p) at a station we mean, that out of 100 days, on p days there will be threshold precipitation or more at the station, or in other words we shall be concerned with point probabilities. Keeping this definition in view, we shall try to answer the following questions. What information is more useful in predicting rainfall probability over a station—the flow type or the past weather? Up to what period shall past weather information be superior (or inferior) to the given flow

Table 5. Comparison of $|P_{wi}-P|$, $i=1$, and $|P_T-P|$ for each month and type. The figures in various cells represent the regions for which $|P_{wi}-P|$, $i=1$, $\geqslant |P_T-P|$.

Month	A	B	C	D	E
			Chart type		
June			5, 8		3, 5, 6, 7, 8
July	7	3, 4, 7		7	3, 5, 6, 7, 8, 9
August		5, 7	7	3, 8	3, 6
September			3	5, 6, 8, 9	3, 6, 7, 9, 10

type information? Before comparing the utility of these two types of information in forecasting, we shall remove the contribution of climatology from them. The difference will then also give us an idea as to how much improvement in skill above climatology may result from the use of each type of information, for forecasting precipitation probability. Hence we computed the absolute deviation of the conditional probabilities (P_{wi}) from the climatic probabilities (P), i.e., $|P_{wi}-P|$, and the absolute deviation of the type probabilities from the climatic probabilities, i.e., $|P_T-P|$, where T refers to A, B, C, D and E types, for each station for each month and for the two threshold rainfall values. If for any particular station $|P_{wi}-P|$ corresponding to the ith day is greater (smaller) than $|P_T-P|$ then the information about the weather of the day is superior (inferior) to the SC for forecasting rainfall on the ith day. Although the utility of the two types of information can be best compared for individual stations, for the sake of conciseness in discussion and presentation on the relative usefulness of these two types, the 107 rainfall stations are put under 10 regions (See Fig. 1a). The average values of $|P_{wi}-P|$, where i corresponds to different days, were found by averaging over the region the values of individual stations falling in the region and these were further averaged over the four months. Similarly, the average values of $|P_T-P|$ were found by averaging the individual values corresponding to all types of flow, in all months and for all stations in the region. The average values of $|P_{wi}-P|$ are then plotted against i (in days) for all the regions for both the threshold rainfall criteria (see Fig. 7). The persistence is more for the 2.5 mm threshold criterion than for 10 mm criterion for all regions except region 7 (west coast) where the reverse is true. This is possible since in this region a fall of 2.5 mm can occur on sporadic days due to orographic effects alone and such falls may not persist beyond a couple of days, while a rainfall of 1 cm will generally occur in association with synoptic systems whose influence may last for some days (see Section 5e). A short dash in Fig. 7 represents the average $|P_T-P|$ for the region for the appropriate threshold. It is clear that both thresholds lead to similar results and that the improvement of forecasts by persistence over climatology gradually decreases from the first to the fifth



day. For all regions, persistence probability is better than the SC for forecasting the next day's precipitation. For regions 3, 5, 6 and 9 for the next day and for regions 1, 2 and 8 up to the second day persistence is a better aid than SC in forecasting precipitation probability based on either threshold criteria. For regions 4, 7 and 10 the limit up to which the persistence is better than SC depends on the threshold criterion. For 2.5 (10) mm threshold criterion persistence is better up to 2 (3) days for region 4, 1 (2) days for region 7 and 2 (4) days for region 10. Beyond these limits SC will perform better if the circulation patterns are correctly forecast.

This is contrary to our expectations that synoptic climatology may turn out a better aid than persistence in forecasting next day's precipitation. Indeed, some types in some months for some regions prove better than persistence but this better aspect of SC has been masked by averaging the value of $|P_T-P|$ over types and months since a greater number of types show less $|P_T-P|$ as compared to $|P_{wi}-P|$, $i=1$. All the regions for which $|P_T-P|$, $T=A$, B, C, D or E $\geqslant |P_{wi}-P|$,

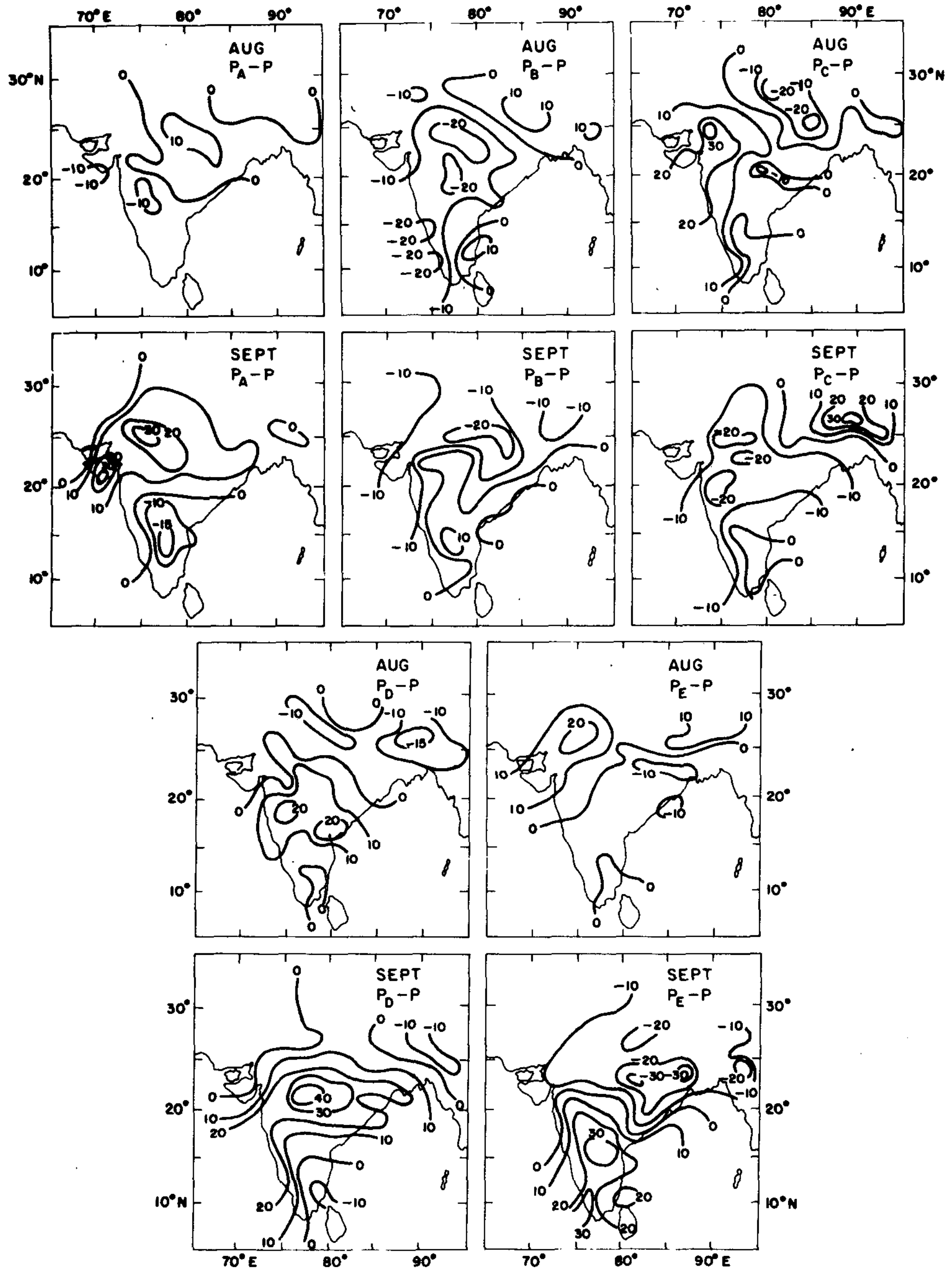


FIG. 6. Difference between type probabilities and climatic probabilities of 2.5 mm or more of 24 h rainfall for each type of contour patterns.

$i=1$ are set out in Table 5, for each month for the 2.5 mm threshold criterion. The total number of figures in the table is 35. This is not a satisfactory figure against a total of 200 possible month-type-regions (month $\times$type$\times$region$=4\times5\times10=200$). It is clear from the table that for the types E(A) the performance of synoptic climatology is better (worse). It may be recalled that while persistence can be used as an aid for forecasting on all days, SC can be used only on days when the observed flow can be identified with any of the types of patterns discussed. While computing the conditional probabilities even the days for which no chart types have been defined, are considered. The persistence effect may vary in various periods conditional to the occurrence of a particular type of pattern. Thus a more appropriate base to compare the utility of SC in forecasting precipitation for the next day will be the double conditional probabilities P_{wT}, $T=$A, B, C, D or E, the probability of recording threshold rain tomorrow, given a type and threshold

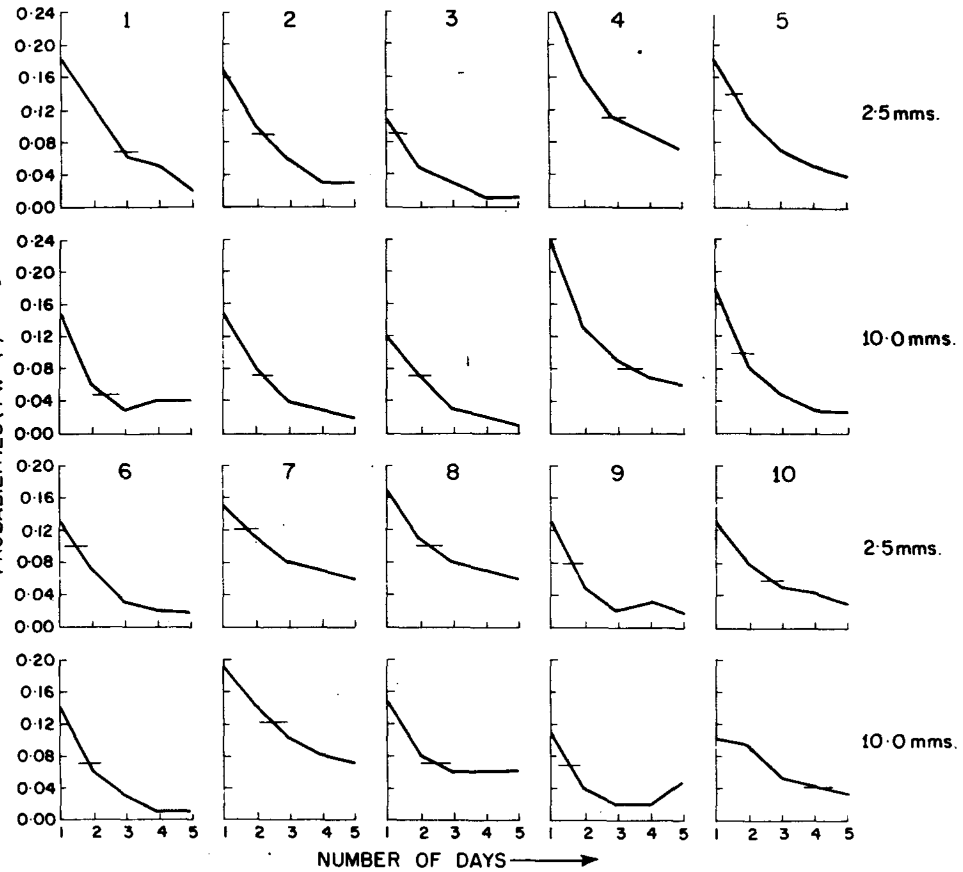


FIG. 7. Averages of absolute values of P_w-P for different regions and days. A horizontal dash on the curve represents the absolute value of improvement over climatology by the synoptic climatology developed in this study.

rain occurring today. These P_{wT}'s are computed for each type, region and month and compared to the P_T's. On construction of a table similar to Table 5 (not shown), it is found that for 45 month-type-regions $|P_{wT}-P| \geqslant |P_T-P|$. This is not a significant improvement over the earlier figure of 35. Persistence is thus in general a better aid for forecasting precipitation probability on next day (day 1 in Fig. 7). One of the reasons for this is that all the charts included in a category are not identical to each other but differ in minor details which are quite important in producing precipitation. Also features like curvature and convergence in the wind field and subsynoptic-scale disturbances so important in causing weather, are suppressed by contour analysis and averaging (for 0000 and 1200 GMT). The circulation features at individual stations/regions are not considered in detail but only large-scale circulations over the whole country are considered.

7. Summary and outlook

With this classifying procedure it was possible to identify the major flow types occurring in each month. However, except in the transition months of June and September when the patterns evolve in a particular way associated with the gradual advance or withdrawal of the monsoon over the country, no preferred sequence of evolution of patterns could be identified. Also the patterns showed preference in periods of their occurrence only in the transition months. The patterns showed persistence and evolved into themselves more often than in any other type but a pattern rarely continues to occur beyond 5 days. The individual charts classified are associated with distinct precipitation probability patterns. The stratification achieved in precipitation probability varies from 5 to 80% over the central parts of the country. The information about today's weather as an aid to forecasting rainfall probability on the next day is superior to SC developed here for practically all the regions up to 1–2 days depending on the region, and this situation generally reverses after 2 days.

The constraint on probability of not attaining extreme values in the central parts of the country (0% or 100%) is probably due to the neglect of some parameters important in the precipitation process. Different types of parameters, depending on station, may be used for better definition of atmospheric state over the station. All charts grouped in a particular type are not identical and hence do not make good enough analogs to each other. The relatively rare types C, D and E in which the individual charts are more likely to resemble each other show better stratification than the A or B types which account for a large number of charts (about 60% of the total). The minor differences in circulation features can be partially accounted for by developing regression equations for stratified charts, between contour height distribution and the occurrence or nonoccurrence of rainfall over a station. A better system of regression equations should consider moisture, thermal and circulation parameters likely to affect rainfall over the station. Such a system, if developed from the outputs of numerical models (which can make better forecast of circulation than rainfall), can be used as an efficient forecast system. This technique, known as model output statistics (Glahn and Lowry, 1972), appears to be promising in forecasting precipitation for several days in advance.

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REFERENCES

Abe, K., 1972: An objective classification of map patterns over Japan in the summer season. *Pap. Meteor. Geophys.*, **23**, 225–240.

Blasing, T. J., 1975: A comparison of map patterns correlation and principal component eigenvector methods for analysing climatic anomaly patterns. *Preprints Fourth Conf. Probability and Statistics in the Atmospheric Sciences*, Amer. Meteor. Soc., 96–101.

Brooks, C. E. P., and N. Carruthers, 1953: *Handbook of Statistical Methods in Meteorology*. M.O. 538, Her Majesty's Stationary Office, 227–228.

Glahn, H. R., and D. A. Lowry, 1972: The use of model output statistics (MOS) in objective weather forecasting. *J. Appl. Meteor.*, **11**, 1203–1211.

India Meterological Department, 1971: *Rainfall Atlas of India*. Poona, 67 pp.

Knowles, H. T., and K. H. Jehn, 1975: A central Texas synoptic climatology and its use as a precipitation forecast tool. *Mon. Wea. Rev.*, **103**, 730–736.

Lal, S. S. and N. C. RaiSircar, 1960: A monsoon storm as studied on 5-day mean charts. *Ind. J. Meteor. Geophys.*, **11**, 268–275.

Lund, I. A., 1963: Map pattern classification by statistical methods. *J. Appl. Meteor.*, **2**, 56–65.

Maxwell, A. E., 1964: *Analysing Qualitative Data*. Methuen & Co. Ltd. (see p. 39).

Murphy, A. H., and R. L. Winkler, 1971: Forecasters and probability forecasts, the response to a questionnaire. *Bull. Amer. Meteor. Soc.*, **52**, 158–165.

Paegle, J. N., and P. Keirulff, 1974: Synoptic climatology of 500 mb winter flow types. *J. Appl. Meteor.*, **13**, 213–220.

Veigas, K. W., 1966: The development of a statistical-physical hurricane prediction model. Final Rep., Contract CWb-10966, The Travelers Research Corporation, Hartford, Conn., 19 pp.