

## Radar-climatology of Delhi and neighbourhood : spatial and diurnal variations of precipitation echo distribution

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**ABSTRACT.** The paper presents a radar-climatological analysis of the New Delhi radar data for a period of 31 months (December 1957 to June 1960). The object is to investigate the space and time variations of precipitation echo distribution within a range of 200 miles round the radar station. The distribution of areal coverage as well as that of the heights of precipitation echoes in the area have been studied both on a month-by-month and a seasonal basis. The diurnal variations of areal and height distributions have also been studied for all the months.

### 1. Introduction

1.1. Until the advent of weather radars, climatological studies had been limited to the extrapolation from data recorded by widely scattered observing stations. Such a process of extrapolation and/or interpolation might be acceptable for such weather elements as temperature, wind, etc but may not be very satisfactory for studies concerned with the occurrence and distribution of precipitation. Obviously, precipitation cannot be extrapolated very far even in a topographically uniform region. There is a practical limit to the density of rain-reporting network and thus no available rain-reporting network can match the performance of a well maintained weather radar. Radar is thus an indispensable tool for precipitation studies.

1.2. Radar, being a relatively new meteorological tool, is not presently being used as a routine source of comprehensive climatological studies. But it has a strong potential for such use. Radar weather observations are capable of providing the following climatological information concerning the region covered by the radar.

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| 1.2.1. Occurrence or non-occurrence of precipitation echoes   | 1.2.2. Spatial, diurnal and seasonal variations of precipitation occurrence                            |
| 1.2.3. Characteristics of precipitation echoes such as : (a) Average duration of cells, (b) Average vertical extent of cells, (c) Average width of frontal formations, (d) Most frequent direction of approach of frontal formations, and (e) Frequency of development of frontal or squall-line activity | 1.2.4. Estimation of seasonal variations of rainfall intensity (after proper calibration of the radar) |
| 1.2.5. Effect of terrain features on rainfall in different seasons and under different synoptic situations  | 1.2.6. Location of favoured regions for echo development   |
| 1.2.7. Comparative study of echo development characteristics over land and over water areas   | 1.2.8. Seasonal variations in the height of freezing level   |

- 1.2.9. Association of severe storm activity with the penetration of tropopause by thunderclouds
- 1.2.10. Characteristics and frequency of phenomena like anomalous propagation with special emphasis on the time of appearance, duration, preferred areas of formation and relation with thunderstorm occurrence.

1.3. This list is by no means exhaustive as there can be many additional climatological studies which can be conducted with radar data. This is because much of the information obtainable from routine radar observations can be converted to climatological data. If properly analysed, most of radar data lend themselves to reduction to a frequency distribution and can even be transferred to punch cards to be handled as any other climatological data by simple statistical techniques.

1.4. In India, so far no systematic radar-climatological studies have been attempted except for the studies of heights of echo tops of thunderclouds over Delhi and neighbourhood by Kulshrestha (1961, 1962) and by Seshadri (1963). Previous to these, Venkateswara Rao *et al.* (1961) had studied the development and movement of thunderstorms in the vicinity of Madras in monsoon season but their study was based only on the data collected during the one season, *viz.*, the monsoon of 1959.

1.5. Systematic studies of various radar-climatological features of the region covered by the powerful radar AN/CPS-9 at New Delhi have been in progress for sometime and the present authors propose to bring out a series of papers describing and discussing the radar-climatology of the region. The present paper is the first one of the series.

## 2. Brief description of the climatology of the region

2.1. Before we describe the radar-climatology of Delhi and neighbourhood, it

is considered desirable to give a brief idea of the climatology of the region.

2.2. Delhi (latitude 28°35' N and longitude 77°12' E), with an average altitude of 210 metres above sea level, is situated in a region which has been variously classified as Monsoon and Upland Savanna or Dry Subhumid. The climate of this area clearly shows the influence of its inland position in a monsoon region. The day temperatures, on the mean, are highest in May but the monthly mean temperatures are highest in June when night temperatures are also the highest. The coldest month is January. The diurnal range of temperature at Delhi varies from 14°C to 17°C during the relatively dry months of October to May to 8°C during July and August. The highest and lowest temperatures ever recorded at Delhi are 47.2°C and -0.6°C respectively. The air over the region is dry for most part of the year and specially so during April to June.

## 3. Scope of the present study : Data used and the manner of its analysis and presentation

3.1. The high power radar AN/CPS-9 has a maximum range of 400 statute miles. Due to limitations imposed by the curvature of earth and by the large attenuation and dissipation of radar energy (specially so on 3-cm wavelength) in the tropics, it is considered a fair estimate that all precipitation echoes, occurring within a range of 200 statute miles, must be recorded by the radar. Actual experience of the past 6 to 7 years proves that this assumption is fairly correct. Thus the present radar-climatological study applies to a circular area of about 1,25,000 square miles round Delhi and the phrase "Delhi and neighbourhood" is taken to denote this area in the present paper.

3.2. The analysis is based on the data acquired during a period of 31 months from December 1957 to June 1960. This period was chosen as this was the largest period for which uninterrupted radar observations were available in 1962 when the present analysis was commenced. During this

31-month period, there were 6841 radar observations and these observations provided the basic data source for the study.

3.3. The year has been broadly divided into the following four seasons for the purpose of the analysis—

December to February	Winter
March to May	Summer
June to September	Monsoon
October to November	Post-monsoon

3.4. For purposes of the analysis of the areal distribution, the area (upto a range of 200 miles round the station) was divided into 192 sectors—each sector bound by a 15° radial line and 25-mile concentric range rings. These sectors were used for computing the frequencies of occurrence of precipitation echoes.

3.5. It will be seen that all the sectors were not of the same area. The area of sectors increased with increasing range. This was purposely done. It is well-known that the detection capabilities of a radar beam decrease with increase in range. In fact, the returned echo power varies inversely as the square of the range. This effect is partially offset, in the present scheme of analysis, by the increasing area of the sectors as the range increases. Therefore, in order to make the frequencies in different sectors comparable, the only alternative was to increase the area of successive sectors with the increase in range. This is why the region was divided into sectors, with their areas increasing successively, rather than in equal-area squares.

3.6. Each radar observation was plotted on a "perspex" diagram and the frequency of coverage of sector by precipitation echoes was noted. Non-precipitation echoes were excluded. A sector was counted as fully covered if it was half or more covered by precipitation echoes. The analysis was carried on for every month of the 31-month period of study and percentage frequencies

of occurrence of precipitation echoes in a particular sector were calculated. These figures give the percentage changes of a sector being covered by precipitation echoes in a radar observation in a particular month. Next, average percentage frequencies were calculated for each calendar month. These were then combined to yield seasonal percentage frequency distributions for the four seasons.

3.7. For purposes of the analysis of distribution of heights of tops, only the maximum height recorded was analysed. It was seen during the course of the analysis that tops of almost all precipitation echoes in the region reached beyond 20,000 feet. Because of this, the height-analysis was carried out only for those echoes whose tops crossed beyond 20,000 feet. There were 469 such cases during the 31-month period of this study. It may be correct to say that the height-analysis in the present study was confined to a very large extent to the convective echoes.

3.8. The heights were corrected for errors due to the curvature of the earth but not for those due to the beamwidth effects. That is why, comparatively larger height-intervals (10,000 ft) were chosen.

3.9. Diurnal variations were studied for areal coverage as well as for maximum height attainment. For this purpose, a day was divided into six significant periods, each of four-hour duration, as follows—

Early morning 00-04 IST	Afternoon 12-16 IST
Morning 04-08	Evening 16-20
Noon 08-12	Night 20-24

#### 4. Space variations of Precipitation Echo Distribution

4.1. The importance of this study lies in the small scale and close-range climatological analysis made possible for the first time through the agency of a powerful radar.

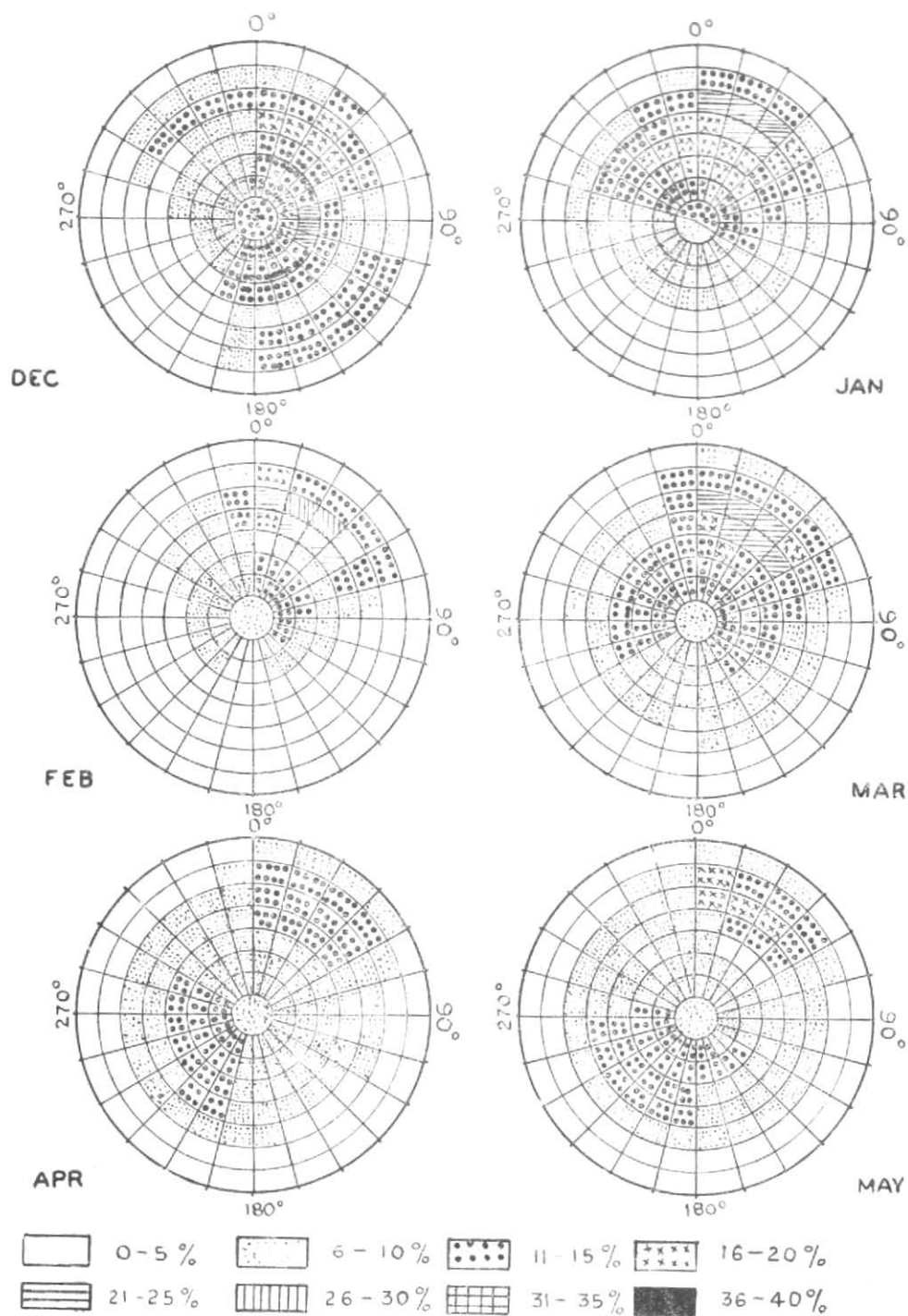


Fig. 1. Monthly percentage frequencies of occurrence of echoes in different sectors

At the same time, it is difficult to describe in words the characteristic pattern shown and the variations exhibited by each of the 192 sectors in which the project area is divided for the purposes of the study. These can best be appreciated by seeing Figs. 1 to 5. Nevertheless, the important features are described below.

#### 4.2. Areal distribution

##### 4.2.1. General features

A close study of Figs. 1 and 2 reveals the following general features of the areal distribution of precipitation echoes in the neighbourhood of Delhi.

4.2.1.1. The area to the northeast of Delhi—between  $000^{\circ}$  and  $060^{\circ}$  azimuth and between 100 to 175 miles—is the region having the maximum frequency of occurrence of precipitation echoes. This is true for all the months. In this connection, it may be remembered that this is in the direction of the Himalayan range. Ground elevation starts rising beyond about 100 miles from Delhi and rises steadily reaching the Himalayan foothills near about 175 miles. It is thought that this orography is largely responsible for the high rate of occurrence of precipitation echoes in this region.

4.2.1.2. It is also worthy of note that the maximum percentage frequency of echo occurrence for any month does not exceed 40 per cent. This means that the maximum chances that a particularly vulnerable sector has of being filled by radar echo in any observation is of the order of 40 per cent only. Thus even during the widespread-rain months of monsoon season, there is no sector in which the chances of precipitation echo are more than 40 per cent for any observation. In the months of April and November, this value is as low as 11 to 15 per cent.

4.2.2. *Month-by-month pattern* (see Figs. 1 and 2)

Many interesting features come to light

when areal distribution pattern is studied month by month.

4.2.2.1. *December*—Precipitation echoes show a tendency to concentrate in the eastern half of the area and in the north-west sectors as well. The west and south-west regions remain almost echo-free. This pattern is due to the movement of western disturbances and their secondaries across the area.

4.2.2.2. *January*—The frequency of echo occurrence shows a decreasing trend in the south and southeast sectors while there is a slight increase in the western sectors. The southwest sector remains almost echo-free as in the month of December.

4.2.2.3. *February*—There is a further decrease in the south and southeastern sectors. The eastern, western and north-western sectors also register a decrease in the frequency of echo occurrence while there is an increase in the frequencies in the northeastern sectors. This confinement of precipitation occurrence to northern sectors is the result of the more northerly disposition of western disturbance tracks in February as compared to January.

4.2.2.4. *March*—The frequency of precipitation occurrence gets more or less uniformly distributed in the region. This is the transition period when the surface pressure distribution over the area is very diffuse and local convective processes have started becoming effective due to appreciable insolation. This is the start of the air-mass thunderstorms over the area. These thunderstorms are naturally randomly distributed in the area and result in the uniformly distributed frequency pattern for March. Due to the orographic effects in the northeast, there is an increase in frequency in that sector. The western disturbances, passing across the north of the country, continue to influence the area and result in the increase of frequency of precipitation echoes in the northwest sectors.

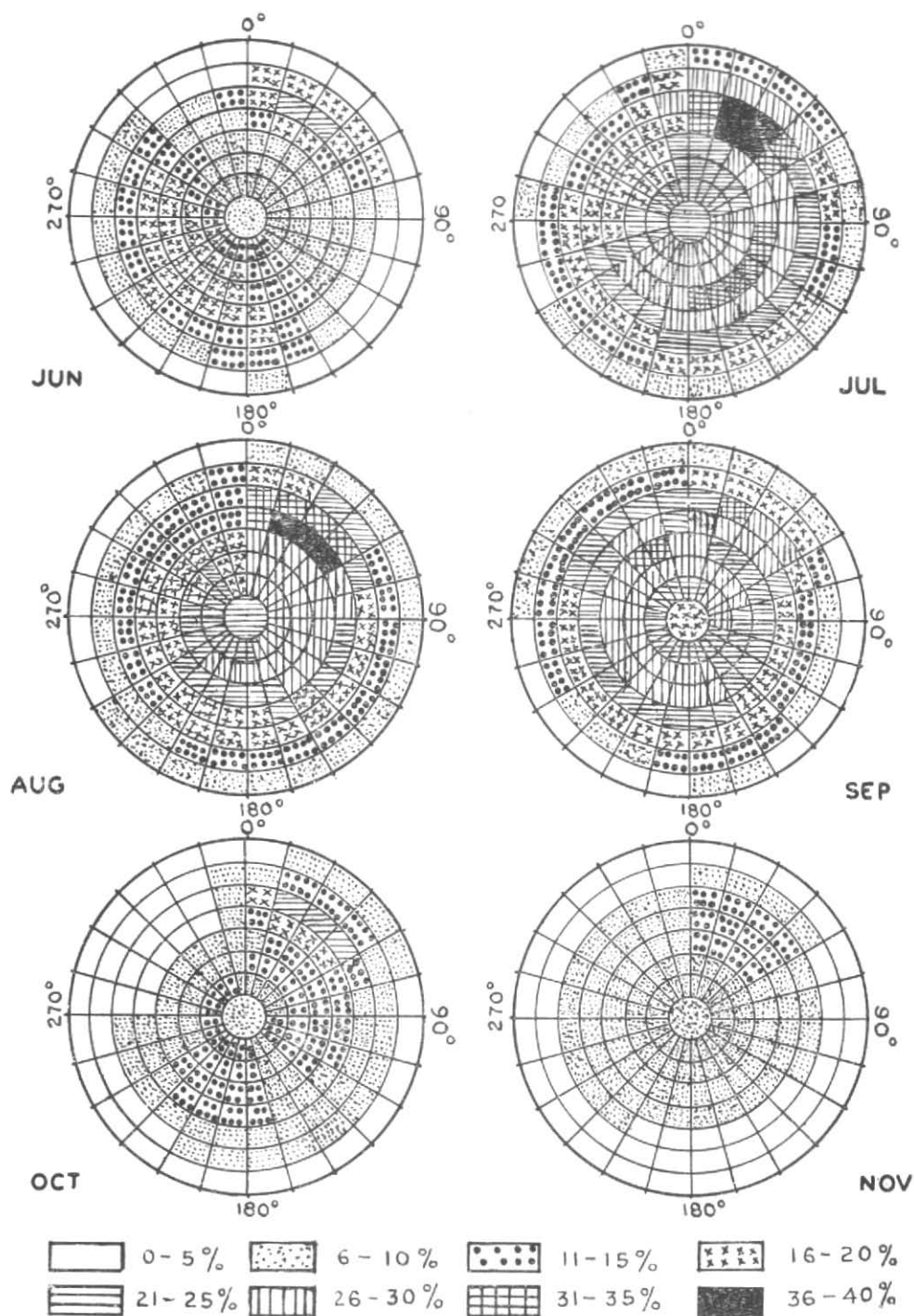


Fig. 2. Monthly percentage frequencies of occurrence of echoes in different sectors

4.2.2.5. *April*—The effect of the western disturbances has decreased effectively and almost all precipitation echoes are due to the air-mass thunderstorms (which have by now assumed the form of duststorms due to the loose sand and dust available in this hot weather period) and are, therefore, randomly distributed in the area. This results in the uniformly distributed frequency pattern. There is, however, a slight increase in the frequency of precipitation occurrence in the southwest sectors. This is due to the incursion of moisture over Rajasthan due to the depressions or cyclones in the north Arabian Sea in this season. The western disturbance tracks have by now shifted further north of the country and there is an appreciable decrease in the frequency of precipitation echo occurrence in the northwest sectors.

4.2.2.6. *May*—The same pattern continues. The western disturbances are by now completely ineffective in the area and that is why there is a further decrease in the frequencies of precipitation echoes in west and northwest. There is an increase in southwest sectors due to the increased incursion of moisture over Rajasthan. The orographic effect in the northeast maintains itself. In May, there is a very significant echo-free region between  $015^{\circ}$  and  $060^{\circ}$  azimuth and between 75 and 100 miles from Delhi. During the three Mays' of 1958, 1959 and 1960, this area has remained almost echo-free. It is not easily understood why this area of about 2000 square miles remains echo-free in May when all round it, there are appreciable precipitation echoes.

4.2.2.7. *June*—There is no change in the frequency distribution pattern, as compared to that in May, except that there is an increase in frequency of occurrence in all the sectors. This is due to the increase in the available moisture in the atmosphere over the area. This is the time when the small echo cells of the hot weather period start showing an increase in horizontal extent (Mitra and Kulshrestha 1961).

4.2.2.8. *July*—The pattern shows certain interesting features. The southwest monsoon advances over the region in late-June and breaks over Delhi by the end of June or the first week of July. The axis of the monsoon trough is mostly in the neighbourhood of Delhi or to the north of Delhi. As is well known, most of the monsoon rainfall takes place to the south of this axis. The July pattern of distribution of frequencies of occurrence of precipitation echoes exhibits these characteristics very clearly. There is an all-round increase in frequencies as compared to June except that there is no large change towards northwest away from the station. This is because the monsoon settles over the Punjab about the last week of July only.

4.2.2.9. *August*—The highest frequencies are exhibited in August. Monsoon is by now well settled over the region and there is widespread rainfall activity over the entire area. This should lead to an overall increase in precipitation and hence in the observed frequencies of precipitation occurrence. By this time, monsoon has settled over the Punjab also and, therefore, the frequencies should have increased in the northwest sectors as well (as compared with the July pattern). But this effect is not clearly brought out in the diagram because of attenuation in the nearby ranges due to heavy precipitation in this month. The higher concentration of frequencies in the eastern half of the region is maintained.

4.2.2.10. *September*—This month exhibits the general monsoon pattern with the frequencies more or less uniformly distributed over the region. Just like August, the whole region is covered by rainfall in this month also.

4.2.2.11. *October*—There is an appreciable decrease in the frequencies over the entire region. In fact, the monsoon withdraws from the entire region by the end of September.

4.2.2.12. *November*—There is a further decrease in the frequencies. In fact, this

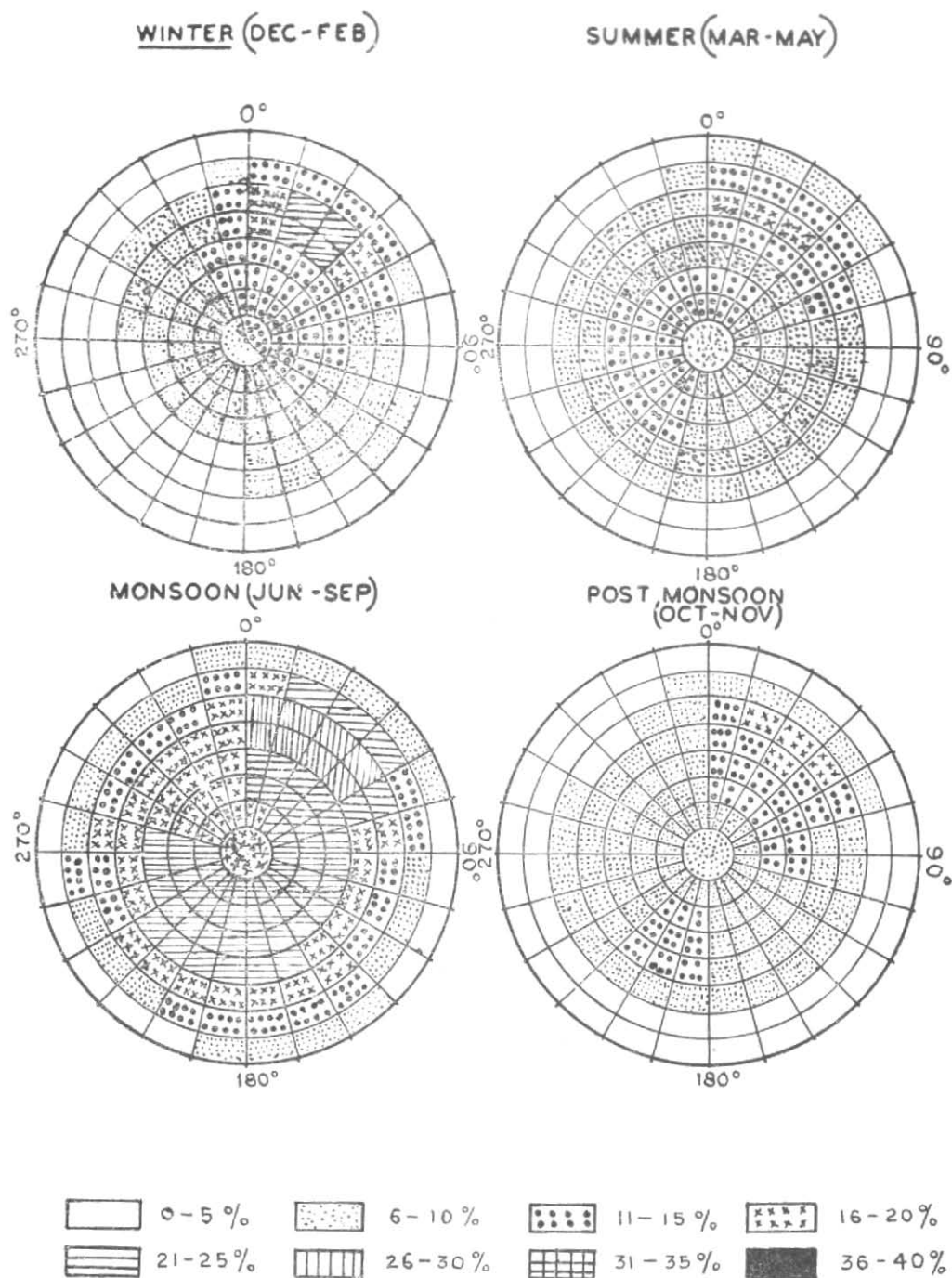


Fig. 3. Seasonal percentage of frequencies of occurrence of echoes in different sectors



is the month exhibiting the smallest frequencies during the year. The distribution of frequencies is also diffuse and almost uniformly distributed round the station with slight increase in the northeast due to orographic effects.

#### 4.2.3. Seasonal distribution pattern

4.2.3.1. In the preceding paragraphs, we have described the month-by-month variations of frequencies of precipitation occurrence on the basis of Figs. 1 and 2. The monthly frequencies have been added up and averaged to yield seasonal variations of the frequency distribution. These are shown in Fig. 3.

4.2.3.2. As one would expect, much of the details are averaged out. Nevertheless, there are certain important features which are described below.

4.2.3.3. *Winter*—The largest frequencies are in the northeast sector followed by those in the northwest and southeast sectors. Frequencies are smallest in the southwest sector. This pattern is due to the effect of western disturbances moving across north of the country.

4.2.3.4. *Summer*—The frequencies are almost uniformly distributed in the area. This effect is due to the air-mass thunderstorms which occur randomly over the area.

4.2.3.5. *Monsoon*—The frequencies again, because of the influence of heavy monsoon activity, are almost uniformly distributed over the region except in the northwest where they are slightly smaller. The sectors in the southwest receive copious amounts of rainfall due to the monsoon depressions while those in the northeast get frequent falls due to orographic effects and also due to the northward shift of the axis of the monsoon trough. The northwest sector, which is not influenced by orographic effects, exhibits smaller frequencies of occurrence of precipitation for reasons already stated earlier.

4.2.3.6. *Post-monsoon*—In this season, the weather over the region is settled. The precipitation is due to certain late monsoon depressions in October or due to early western disturbances in November. The frequencies of precipitation echo occurrence are small and uniformly distributed in the region except in the northeast where orographic effects tend to increase the frequencies somewhat.

#### 4.3. Distribution of heights of echo tops

4.3.1. It was noticed during the analysis of the distribution of heights of echo tops that almost all the precipitation echoes observed in the region had their tops going beyond 20,000 ft above ground.

4.3.2. Fig. 4 illustrates the frequency distribution of heights of tops of precipitation echoes around Delhi and gives the numbers of echoes falling in each height group or height-interval in the various months. This histogram also depicts the month-by-month variation in the maximum heights attained by precipitation echoes. It is significant to note that the maximum number of precipitation echoes occur in the region in the monsoon season (as seen from Figs. 1 to 3) when the heights of tops of the echoes are also the largest (as seen from Fig. 4). The post-monsoon season has the least number of precipitation echoes (Fig. 3) but the heights are the smallest in winter (Fig. 4).

#### 5. Diurnal variations of precipitation echo distribution

5.1. Diurnal variations of precipitation echo distribution were studied with respect to both the areal coverage as well as the maximum height distribution. An attempt was made to find out if there are any preferred periods of attainment of maximum areal coverage and of maximum heights. For this purpose, a day was divided into the six significant periods of four hours each as already mentioned in section 3.9. For the study of the diurnal variation of areal

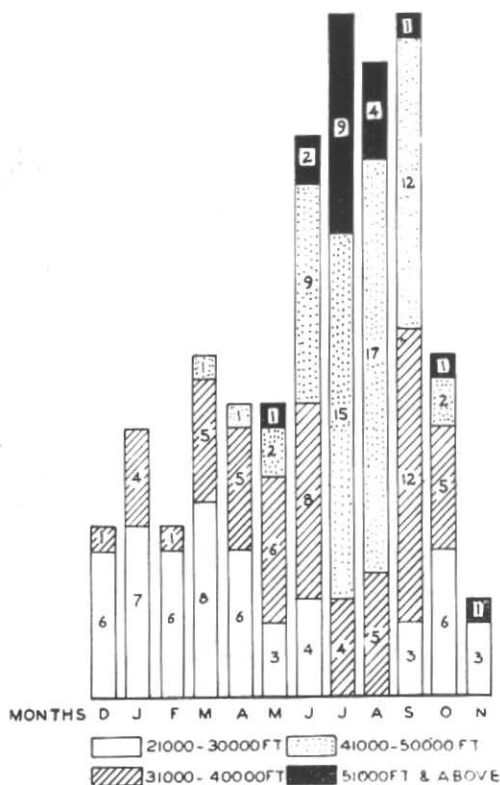


Fig. 4. Monthly distribution of heights of echo tops

coverage, the average number of sectors covered in any radar observation in each of the six significant periods during a particular month was found out. For the study of the diurnal variation of the maximum height distribution, the average number of occasions when the maximum height is reached during a particular time-interval was found out for each month. These two sets of monthly curves (one for the areal coverage distribution and the other for the maximum height distribution) were plotted together and are given in Fig. 5.

### 5.2. Diurnal variations of areal distribution

5.2.1. It will be seen from Fig. 5 that the time of the occurrence of maximum areal coverage is mostly in the afternoons or evenings, *i.e.*, between 1200 and 2000 IST. In fact, there are five months, *viz.*, December, July, August, September and October, in which the maximum areal coverage occurs in the afternoons, *i.e.*, between 12 and 16 hrs IST. In four months, *viz.*, April, May, June and November, the maximum areal coverage occurs in the evenings, *i.e.*, between 16 and 20 hrs IST. In January and February, the maximum areal coverage takes place in noon (08-12 IST) and morning (04-08 IST) respectively. March shows a peculiar characteristic. Here there are equal number of sectors covered in the night (20-24 IST) and in the early morning (00-04 IST). It is, therefore, reasonable to conclude that in March the maximum areal coverage occurs at about midnight.

5.2.2. While these results are quite significant in themselves, very interesting aspects are brought out if the seasonal trend of shift of the time of maximum areal coverage is studied. Beginning with the start of winter season, the time of maximum areal coverage lies between 12 and 16 IST (afternoon) in December. In January, this shifts to the just preceding period, *viz.*, noon (08-12 IST). In the next month, *i.e.*, in February, the time of maximum areal coverage further shifts to morning hours (04-08 IST).

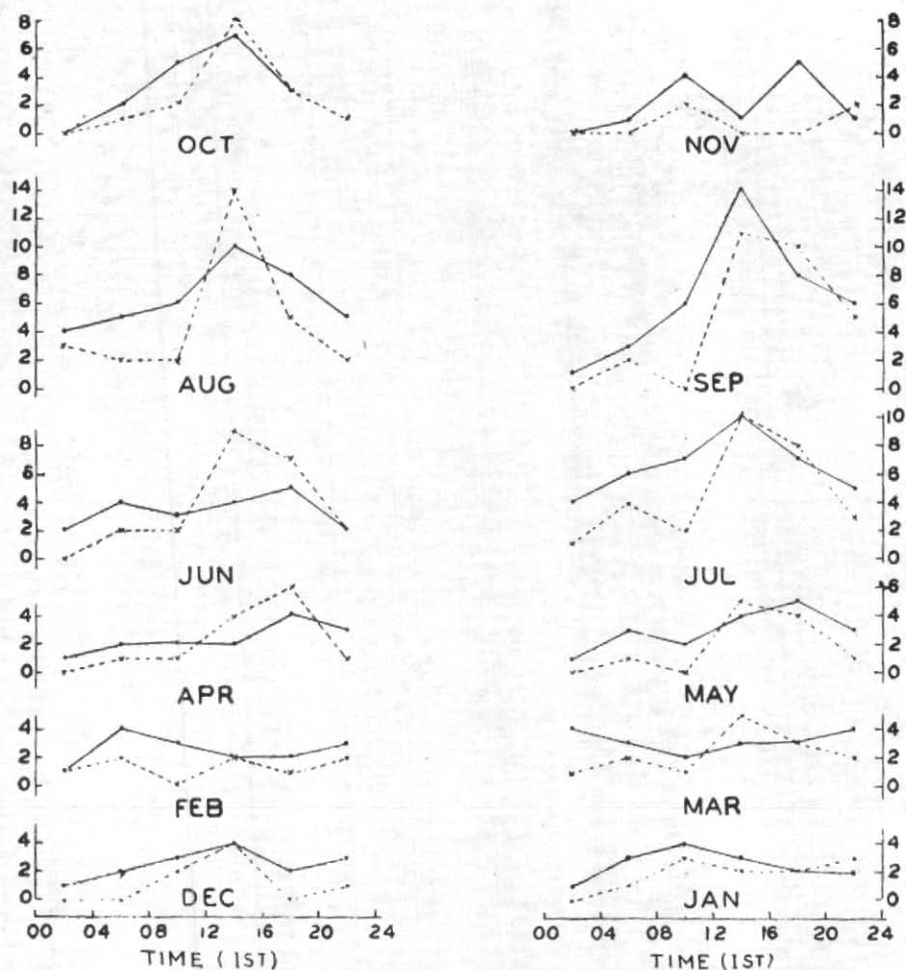


Fig. 5. Diurnal variation of areal coverage and maximum heights of radar echoes

— Average number of sectors covered in any radar observation during the time-interval  
 - - - Average number of occasions when the maximum height is reached during the time-interval

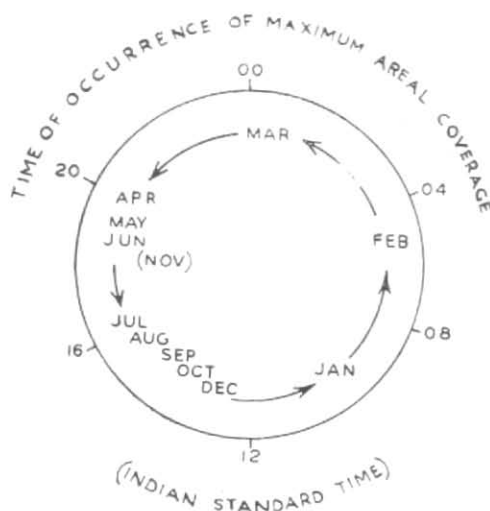


Fig. 6

During March, it shifts to about midnight as discussed in the preceding paragraph. The month of April finds that the time of maximum areal coverage has further shifted to evening (16-20 IST). During May and June, it maintains itself and then shifts to afternoon (12-16 IST) in July where it maintains itself in August, September and October. November is the only month which does not fit in this trend and in fact shows a maximum of areal coverage in the evenings, *i.e.*, between 16 and 20 hrs IST.

5.2.3. This trend cycle can be diagrammatically represented as in Fig. 6. November is the only month which does not fit in the trend. According to Fig. 6, November should have the maximum areal coverage between 12 and 16 IST but it will be seen from Fig. 5 that during this time-interval, November shows a definite minimum which cannot be ignored. It is likely that because of November being a fine weather period for the region, it does not follow any particular trend. But the rest of the months ex-

hibit an interesting cycle of trends as shown pictorially in Fig. 6 and discussed above.

### 5.3. Diurnal variation of maximum height distribution

5.3.1. It will be seen from Fig. 5 that in about 8 or 9 months in a year, the maximum heights are attained in the afternoons, *i.e.*, between 12 and 16 IST. These months are December, March and May to October. In February, the maximum heights may be attained either between 04 and 08 IST or between 12 and 16 IST. During November and January, the preferred period is either 08 to 12 IST or 20 to 24 IST. There is no instance of maximum heights being attained in the early morning hours, *i.e.*, between 00 and 04 IST.

5.3.2. No monthly trend of shift of the time of attainment of maximum heights is observed but it is interesting to note that in as many as three months (*viz.*, January, February and November), there are two preferred periods of attainment of maximum heights.

#### 5.4. Correspondence between diurnal variation of areal distribution and that of maximum height distribution

5.4.1. It will be observed from Fig. 5 that there is a resemblance between the two sets of curves. The maximum areal coverage and the maximum heights occur in the same time interval or neighbouring time intervals.

#### 6. Advantages and limitations of the present study

6.1. As already mentioned, this is the first attempt at the systematic study of the radar-climatology of Delhi and the neighbourhood. Since it pertains to an area of 200-mile range, that is more than 1,25,000 square miles, round Delhi, it is reasonable to regard the study as representative of the radar-climatological conditions of north India. The object of this study has been to observe and arrange, in a climatological sense, the spatial (areal and vertical) and time variations of precipitation echo distribution in the region. The advantages of such a study are obvious. This provides, for the first time, a study of precipitation distribution in space and time on a meso-scale and also its month-by-month and seasonal variations. The usefulness of such a study cannot be over-emphasised. Apart from its academic value, it provides a ready reference material on a space and time scale. It brings out the precipitation-potential areas for different seasons and will, therefore, be found to be a useful guidance material to forecasters and hydrologists alike. It tells them the areas that are particularly vulnerable to precipitation occurrence. It also provides an equivalent of the conventional "normals" which can be usefully utilised either to plan the frequency of radar operation or even as substitute for radar observations when radar might be out of commission—a situation which is not infrequent.

6.2. At the same time, it cannot also be overlooked that the present study suffers from a series of limitations too. The first and the foremost is the wavelength of the radar. It was 3 cm and it is well known that atten-

uation on this band is quite appreciable when there are intervening areas of heavy precipitation. This limitation was to some extent compensated by the high power (250 kw) of the radar AN/CPS-9,

6.3. The results derived in this study are by no means final; additional data may modify these findings. What the authors have tried to present are their findings at this stage. Like any other climatological normals, the spatial and diurnal variation of precipitation echo distribution over the region has also to be treated as a continuing investigation and, therefore, subject to periodic modification (if necessary) as more data become available.

#### 7. Conclusions

The main conclusions of the present study may briefly be summarised as follows—

7.1. The areal distribution of precipitation echoes in an area of 200-mile range round Delhi has been studied and polar diagrams have been plotted showing the average percentage frequencies of occurrence of precipitation echoes in different sectors in any month.

7.2. Similar diagrams, showing the seasonal percentage frequencies of occurrence of precipitation echoes in different sectors, have been prepared for the four seasons, *viz.*, winter, summer, monsoon, and post-monsoon.

7.3. The characteristics of these distributions have been brought out.

7.4. The distribution of maximum heights of echo tops during different months has been studied and presented in the form of a suitable histogram.

7.5. The time variation of areal coverage has been studied for every month and the diurnal variation of areal coverage is presented for each month.

7.6. It was found that the time of occurrence of maximum areal coverage follows an annual trend, which has been diagrammatically presented.

7.7. The time variation of attainment of maximum heights has been studied for each month. It was found that there is a close resemblance between the pattern of diurnal variation of areal coverage and that of the attainment of maximum heights although the latter does not exhibit any regular trend as in the case of the time of occurrence

of maximum areal coverage.

#### 8. Acknowledgement

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