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Incidence of 'warm' and 'cold' rain in and around Delhi, and their contributions to season's rainfall

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ABSTRACT. Based on study, using radar, of frequency distribution of rain cells of different types, classified according to their vertical structures, their average areal extents, and associated mean rates of precipitation, an attempt has been made to estimate the relative contribution of 'warm' and 'cold' rain to natural rainfall over the area around Delhi, in northwest India, in different seasons. It is seen that, while occurrences of rain from warm clouds in the area generally are by no means infrequent, particularly during southwest monsoon season, the actual yield of such rain is quite small. On the basis of data collected, possibilities of rain augmentation in the region by warm seeding techniques have been considered in a general way.

1. Introduction

That rain development in certain situations can occur by water process alone, without intervention of ice crystal mechanisms as postulated by Bergeron (1935) and Findeisen (1939), is well confirmed by direct observation from aircraft and also by studies made with the help of radar. Indeed, numerous reports have been received, particularly from tropical maritime regions, about moderate rain falling from clouds lying wholly below freezing level, according to some (Leopold and Halstead 1948) of which the bulk of rainfall in such areas is the result of rain showers from warm convective clouds. In view of these reports, and considering that as low clouds over the tropics which are tall enough to extend to beyond freezing level (occurring generally at a great height) would almost invariably give rain by natural processes, artificial rainmaking projects in tropical countries have, as a rule, been based on seeding techniques applicable mainly to warm clouds. Recent rainmaking trials at Delhi, using a method of dispersal of salt seeds of appropriate sizes from ground, aim chiefly at stimulating rain in warm clouds by seeking to modify their micro-structure when this happens to be unfavourable.

In relation to such projects of artificial augmentation of rain in an area by methods of warm cloud seeding, it would naturally be of interest to consider how much net increase in a season's rainfall could possibly be effected by such means, even if the contemplated technique could be applied successfully to all situations of development of clouds of the right type. For attempting an answer to this question we would need information on the following points:

(*i*) proportions of natural rainfall as occur in the area from warm clouds during different seasons,

(*ii*) types of meteorological situations which specially favour warm rain development in the area, and

(*iii*) percentage of warm clouds having adequate depth, from which rain occurs naturally.

While a planned programme of cloud census, by systematic aircraft observation of height, depth and rain-giving of clouds, would be necessary for collecting data required for (*iii*), much useful information regarding the other two points can be had by a critical study, using radar, of vertical structures of precipitation cells of various types and their relative capacity to yield rain in different rain situations. Studies in regard to these latter aspects have been made of rain cells around Delhi, and preliminary results reported briefly in a note (Roy 1959a) published recently. A more complete account of investigations made is presented in this paper.

2. Radar used for study and method of observation

The radar used is type NMD-451 A, operating on wavelength 3·2 cm and having peak output about 250 KW. Its radiating system consists of a feed-horn and a parabolic reflector two metres in diameter, which shapes the beam to 1° in both azimuth and elevation. The duration of transmitted pulse is one micro-second, and its repetition frequency is 300 per second. Total gain of the receiver is about 110 db.

The instrument is equipped, in addition to the conventional Plan Position (PPI), Range Height (RHI) and Amplitude Modulated (A-scope) indicators, with a special arrangement called Range Elevation Indicator (REI) on which depth and range of echo are portrayed in true proportions when scanned at elevational angles between —1° and 90°. Maximum range of the radar is 360 km on PPI, REI and A-scope, and 100 km on RHI. Range markers 2·5, 5, 10, 20 and 60 km apart are provided in the 10, 20, 50, 100 and 360 km ranges respectively. The RHI is supplied with height markers at intervals of 2·5 and 5 km respectively in its 10 km and 20 km height ranges. The over-all sensitivity of the set is such that it can just detect rain drops of diameter about 0·33 mm at a distance of 100 km, if these are present in concentration of 10 per litre.

Heights of rain cells—Survey, using the radar, has been made of precipitation occurrences within 100 km around Delhi, and data collected on frequency distribution of rain cells grouped according to heights reached by their echo tops. For this, an examination is first made, on the plan position indicator scanning at near zero elevation, of the broad features of rain cells and their distribution within the range stated. The cells are then projected individually on the RHI or REI and the heights of their tops determined, the cells being picked up at random and the number examined depending upon time available for such a study which was limited usually to half an hour to one hour on each occasion. To ensure determination of correct height of the topmost part of rain cell, care is taken so to fix the azimuth of scanning at each elevation that it passes through the brightest portion of echo at that level. This precaution is necessary, as quite frequently it is seen that the azimuth corresponding to highest point of echo from a convective type rain cell is very different from that at which echo is strongest near ground.

Data collected for two monsoon seasons (July to September) of 1958 and 1959, one winter season (mid-November to February) of 1958-59, and two summer seasons (May-June) of 1958 and 1959 combined, are shown in Table 1. Heights given are the maximum reached by echo tops during the period of survey. In particular, height determinations are repeated in case of cells which are limited to below 0°C isotherm, to see if any of these later develop into one of cold type. Table 2 gives height distribution of radar echo tops relative to rain cells in the various seasons. A diagrammatic representation, giving cumulative frequency of rain occurrence plotted against echo heights reached by precipitation echo is shown in Fig. 1.

Associated rain intensities—Precipitation rates have been estimated from observed radar echo intensity, using mean empirical fromula ($Z=242R^{1\cdot42}$) connecting radar reflectivity Z, and rain intensity R, found earlier (Ramana Murty and Gupta 1959) for Delhi rains. Echo intensity is determined on the basis of echo amplitude as shown on the A-scope, which was duly calibrated for the purpose by method described briefly below.

A fiducial line is drawn on the face of the A-scope at a height above base line corresponding to the noise level of the receiver, with gain set at its maximum value. With the gain control knob at this position, a signal of such strength is injected from a standard Hewlett-Packard, Model 620-A, signal generator into the first detector stage of the receiver through the main wave guide of the radar that the output level from the receiver coincides exactly with the fiducial line on the A-scope. The corresponding attenuator reading on the signal generator is

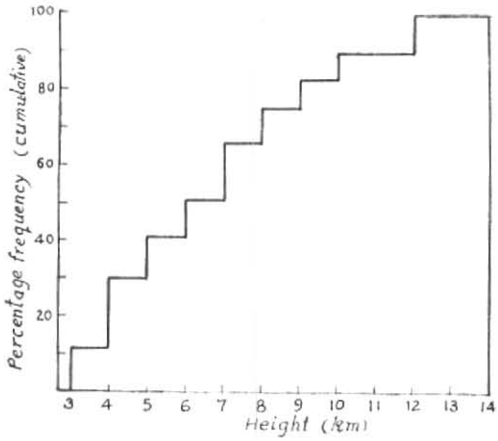

Fig. 1(a). Monsoon of 1958 and 1959 combined

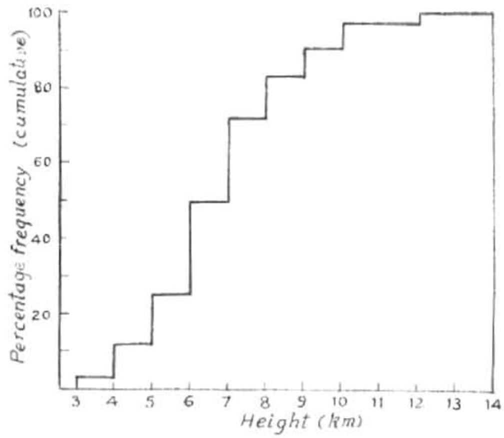

Fig. 1(b). Summer of 1958 and 1959 combined

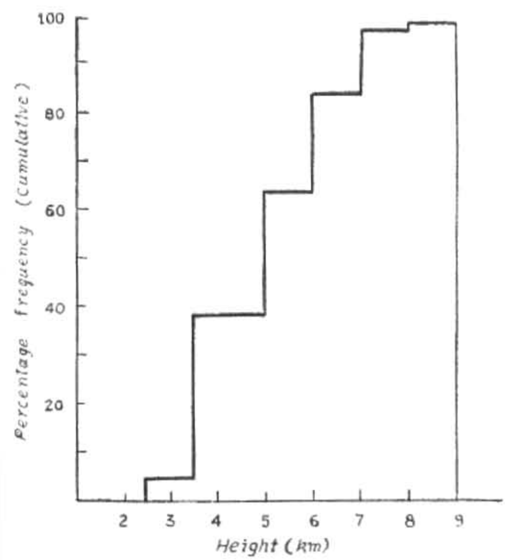

Fig. 1(c). Winter of 1958-59

Fig. 1. Percentage frequency (cumulative) of rain occurrences against heights reached by echo tops

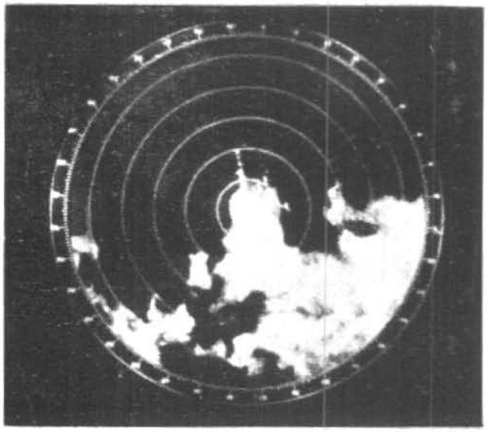

Fig. 2(a). A-class day

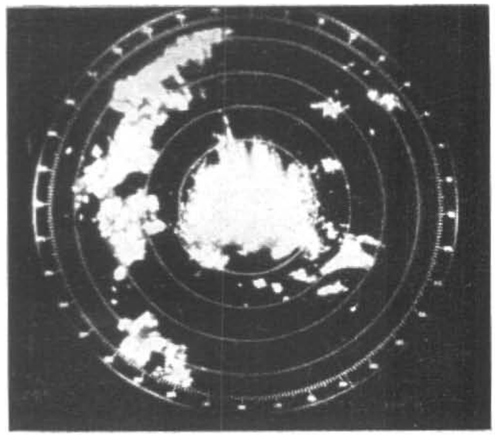

Fig. 2(b). B-class day

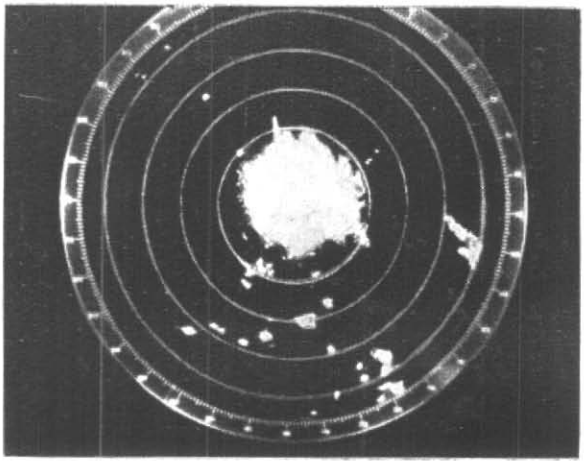

Fig. 2(c). C-class day

Fig. 2. PPI pictures of rain occurrences
Range rings 20 km apart

then noted. Similar determinations are made with the receiver gain set at various other positions. Operations as above are repeated and mean reading relative to each gain position is used for obtaining the required calibration curve. A watch is kept on the constancy of receiver sensitivity by undertaking fresh calibrations from time to time, particularly after each occasion of replacement of valves in the I.F. section of the receiver. From the calibration readings obtained, it is seen that a change in gain setting, from its lowest value at zero mark to the maximum at 9, permits a change of 30 decibels in the signal power level. It is seen that even this range of variation in the sensitivity of the receiver is not adequate for determining the exact value of rainfall rates in Delhi area in all situations. From rainfall rates calculated on the basis of Z, R relation referred to, it is seen that the limits within which rain intensities can be measured with this radar at 10, 25, 50 and 100 km range are between 0·005 and 0·75mm/hr, 0·02 and 3·0 mm/hr, 0·05 and 7·4 mm/hr, and 0·13 and 19·4 mm/hr respectively. Thus, while the lower limits of detectable precipitation rate are quite small, the upper limits are not high enough to permit exact quantitative determinations in certain situations. This is because when echo intensity exceeds a certain value the echo amplitude shown on the A-scope gets flattened, due to the action of the indispensable video limiting amplifier. Because of these limitations, intensity values given in the paper relating to some of the heavy rainfall situations indicate only the lower limits of rainfall rates at certain instants.

Rain intensity determinations by the above method were commenced from November, 1958. Considering various limitations of the method used, the estimates made can only be treated as approximate. Firstly, there is the difficulty of calibrating fully satisfactorily the vertical scale of the A-scope due to fluctuating nature of rain echo. Secondly, there is the uncertainty about exact determination of rain intensity by using the same mean relationship between Z and R in all rain situations, knowing that considerable scatter of Z values occurs depending upon the character of rainfall (Atlas and Chmela 1957) and phase of precipitation at which observation is made. Further, attenuation of radar beam by intervening cloud and precipitation fields is likely to affect determinations in some instances. To minimize errors due to rain attenuation, intensity data collected for purposes of present study have been based on observation of rain cells between which and the radar no other precipitation field intervened. Also, intensity determinations have in each case been made on the basis of means of a number of readings of gain control position.

3. Classification of rain cells and associated rain days

Based on criteria of height of echo top *vis-a-vis* freezing level, and of association or otherwise of cold rain cells with melting band indicative of rain by ice process, precipitating clouds have been classified under three groups a, b and c, and different days on which survey of precipitation features was made with the radar, under classes A, B and C as follows.

a type rain cell	Echo top is well above freezing level, and well developed melting band is seen.
b type rain cell	Echo top is above freezing level, but radar echo shows no melting band structure.
c type rain cell	Echo is confined below freezing height.
A class rain day	Day on which one or more amongst the rain cells is of 'a' type.
B class rain day	Cold rain cells are all of 'b' type.
C class rain day	All rain cells are of 'c' type.

For the monsoon season, when freezing height is normally between 5 and 5·5 km, a rain cell with vertical development less than

6 km is designated as c-type. This limit is taken as 3·5 km for winter, when freezing temperature is reached usually below this height. In tabulating instances of c-type rain cells, care is taken to see that the observed cell is an independent one and is well separated from a more prominent rain cell nearby. Also, in order to eliminate as far as possible inclusion under type-c instances of degenerated cold rain cells at the end stages of their life, only those cases of warm rain occasions have been included in which associated radar echo shows some tendency to gain in height, or at least remains steady for some time.

On the basis of above classifications, frequencies of occurrence of a-, b- and c-type rain cells in and around Delhi have been determined for the three seasons—winter, summer and monsoon, and are shown in Table 3.

4. Prevailing weather features on A, B and C-class days and certain distinguishing characteristics of rain cells of the three types

As stated earlier, a day is treated as under class A if one or more amongst the precipitation cells observed shows evidence of rain by Bergeron mechanism. Prevailing weather features on a day of this class, as indicated by radar and shown on synoptic weather chart, are fairly extensive precipitation fields in and around the area under study, and rain falling steadily from deep layer-type clouds. A typical PPI picture of rain occurrences on such a day is shown in Fig 2(a) (p. 334) which illustrates, besides widespread nature of rain distribution, characteristic fuzzy structure of precipitation echo from stratified-type rain of temperate latitudes. Compared to this, weather on B- and C-class days is showery in character, precipitation occurring temporarily and in a rather scattered manner. From PPI pictures for these two classes of days, in Figs. 2(b) and 2(c) it is seen that the echoes are mostly of a cellular nature with fairly smooth and well defined boundaries, typical of columnar type rain cells associated with convective cloud fields. The main differences noticed between B and C-class days lie in a much higher rate of rainfall and more prolonged showery activity associated with the former—features which are discussed further in a later paragraph. Also, while rain cells on many of the B-class days appear to show a certain regularity in their distributions, shower developments on C-class days are mostly of a random nature.

Based on examination of radiosonde data for Delhi, a study in a general way has been made of thermodynamical structure of the atmosphere on the three classes of rain days during the two monsoon seasons. The features in regard to relative stability of the atmosphere on different days, as shown on the tephigrams, are indicated under 'Remarks' column in Tables 1(a) and 1(b). It is seen that while the atmosphere is relatively stable on days of class A, latent instability to a certain degree is present on most days of B and C classes. The findings are in conformity with what may be expected from the general nature of rainfall and types of clouds associated with the three classes of days under review. Comparative stability and, as such, less turbulent mixing inside cloud allows transition of precipitation elements from ice to water phase to occur smoothly at more or less the same height below freezing level, helping formation and steady retention of well-defined melting band in an a-type rain cell. The findings as above are, however, at variance with those by Day (1953), according to whom days with Bergeron type precipitation in Australia are more frequently associated with atmospheric instability. In this connection, the question as to how far departures of surface pressures from normal could be taken as a criterion for judging atmospheric stability, as has been done by Day, needs consideration.

Precipitation rates and duration—On the basis of echo intensity measurements discussed in an earlier section, estimates have been made of mean rainfall rates associated with precipitation cells belonging to the three classes. Average rates, based on determinations made in a number of rain situations, for the three seasons, monsoon, summer and winter, are given in Table 4(a).

In Tables 4(b) and 4(c) are given some of the details relating to observations made in four rain cells each of b and c type. Mean rates of rainfall in case of these cells have been calculated on the basis of weighted averages of intensities observed at successive intervals, the observation covering practically the entire period of rainfall. In case of a-type rain, however, which continues usually for several hours together, mean rates given have been based on arithmetical averages of rain intensities determined from time to time.

Comparing precipitation durations in b- and c-type rain cells, it is seen that while rain showers from cold convective clouds usually last for half an hour to one hour or more, precipitation from warm clouds is generally short-lived continuing rarely for more than 20 minutes.

Areal coverages of rain cells—For comparative estimate of liability of development, at one given station, of rain of the three types under discussion, we have to have, besides frequency figures of such rain occurrences over the region generally, a knowledge of proportionate areal coverages of these different rain cells. To obtain this, areas covered on PPI scope by a number of rain cells of types a, b and c have been determined, from which it is seen that on the average the areas are in the ratio of 50 : 5 : 1. The mean ratio is found to be nearly the same for all seasons.

5. Relative contributions to season's rainfall by cold and warm clouds

From frequency figures of rain cells under various height groups as in Table 2, and histograms in Fig. 1 it is seen that, except during winter months when rain cells of type-c are of rare occurrence, quite a large proportion (about 30 to 40 per cent) of precipitating clouds in Delhi area belongs to warm type. Consideration of some of the associated features, such as restricted areal coverage of and low rates of precipitation from such cells, however, shows that their actual contributions to rain even during the more favourable seasons, summer and monsoon, may not be substantial. Using data of frequency of occurrence of a-, b-and c-type rain cells in different seasons (Table 3), ratio of their areal extensions discussed in previous section, and their mean rates of precipitation (Table 4a), a fair estimate can be made, on the basis of products of these three factors, of relative contributions to season's total rain by precipitation occurring from clouds of different types, representing respectively rain initiation by Bergeron process, coalescence-cum-ice mechanism, and growth by pure coalescence. Estimated percentage contributions are shown in Table 5.

It is seen that pure coalescence rain as from a warm cloud contributes but little to rainfall in the area under study, the maximum contribution during monsoon months being limited to only about 2 per cent of the season's total. While, in general, the bulk of rainfall is given by cold clovds, that during the two hottest months, May and June, is received from those of b-type only. Absence altogether of a-type rain during summer months is what we would expect from consideration of prevailing synoptic features of the season, when weather is almost invariably of intra-air mass character and predominantly of instability origin. As regards monsoon season, while it is seen, on the basis of combined figures for 1958 and 1959, that the contributions from a-and b-type rain cells are of about the same order, data for two individual years show that their relative shares may differ considerably from one year to another. The observed differences between the two years, namely, preponderance of Bergeron type precipitation during 1958 and of convective rain showers in 1959, can perhaps be explained on the basis of characteristic differences noticed in synoptic weather situations during the two seasons. From a study of weather charts it is seen that, whereas during 1958 the axis of active monsoon trough, separating easterly monsoon air streaming up the Gangetic Valley from fresh monsoon air from west to southwest, ran usually very close to or slightly to the north of Delhi, leading to development frequently of weather processes of a quasi-frontal character, the monsoon trough and, as such, the zone of convergence between the two air masses lay, in general, far to the south of Delhi during 1959. As a result, weather over the area during the last monsoon season was very often in the nature of a single air mass phenomenon, having been helped largely by instability of atmospheric structure. As for winter months, observed greater prominance of rain showers from supercooled convective clouds, compared with precipitation of a-type during the season, when weather processes in northwest India, controlled chiefly by western disturbances, show features somewhat similar to those of extra tropical latitudes, needs explanation. It appears that, with the main western depressions following a track well to the north of Delhi, the area in question does not come always under direct influence of frontal weather systems and that rain occurrences there more often are results of convergence within the same warm moist air mass drawn from more southerly latitudes under influence of these depressions. Also, active weather development leading to rain over the area by frontal mechanism, when this happens to take place, is perhaps more commonly associated with cold fronts, often occluded, rather than warm fronts.

In our discussions of precipitation cells of the three types, we have referred to rain from a type-b cell as being processed by the combined mechanisms of coalescence growth of cloud water droplets in lower warm layers, and of progressive growth by condensation of ice crystals in upper supercooled regions. While it is difficult to estimate the relative contributions of the two mechanisms to rain occurrences of this kind, certain features brought out by studies made with the radar appear to suggest that both these processes play a part in full scale development of such rains. In several instances of raincells developing ultimately to type-b, precipitation echo was detected by radar well before the cell grew to sub-freezing heights, showing that rain formation at least to a limited scale occurred by coalescence process alone. Of the total number of b-type cells discussed in the paper, nearly 15 per cent were found to be precipitating before these had grown to heights above freezing level. A marked increase in rain intensity usually followed this growth later to the stage of a cold cell but this, by itself, cannot be taken as a sufficient indication that Bergeron mechanism actually operated in further development of rain at later stages. On the other hand, it has to be observed that mere absence of melting band feature in a radar echo does not necessarily preclude ice mechanism having played a part. The effects of large scale mixing of precipitation products in ice and water phases in a tall convective cloud with strong vertical currents and severe turbulence, in masking or obliterating the definiteness of intensity structure characteristic of a melting band are well recognised. Further, in a few instances of type-b cell in which determinations of intensity structure were continued till the end or decay stage of shower activity, certain features suggestive of melting band phenomenon have been noticed in the shape of a sharp increase in intensity gradient near about 0°C isotherm level, although corresponding abrupt fall below melting layer is not detectable. A fuller discussion on these and other features of melting band structures associated with rain in different situations is being presented in a separate paper.

6. Possibilities of rain augmentation in Delhi area by methods of warm cloud seeding

In his discussion on 'warm cloud rainfall' in tropical regions, Alpert (1955) having drawn attention to lack of quantitative information in regard to frequency of such rains and the proportion of total rain that falls from these warm clouds, expressed hope that meteorologists working in the tropics would undertake rain cloud census to shed some quantitative light on this important problem. The studies, as in this paper, undertaken with a view to finding an answer to the question, with reference to conditions prevailing well inland in northwestern part of India, have helped to provide certain basic data as may be useful in considering potentialities of warm cloud seeding as a means to augmenting rain in Delhi area. For fuller appreciation of the position, we have also to know what percentage of clouds of adequate depth develop but fail to attain rain stage. In any such attempt at indirect estimate of efficacy of seeding trials, we assume that all cases of precipitation failure in clouds having reached a certain stage of development are due essentially to the deficiency of suitable atmospheric nuclei which we seek to make good by proposed techniques of cloud seeding.

Considering pure coalescence rain as from warm clouds, we have seen that this contributes only about 2 per cent of total rainfall in Delhi area during monsoon months. Taking that this yield of rain is what is received from some 50 per cent of warm clouds which form or pass over a given station, the other half failing to precipitate because of their unfavourable micro-structures, the expected net increase in rain by regular seeding of all clouds would be no more than about 2 per cent of season's total. On the other hand, if natural development of rain in clouds of this kind occurs only in 1 out of 10 instances, one could hope to bring about as much as 18 per cent increased yield by successful seeding of all such clouds. The real position in this regard could only be ascertained by systematic survey, from aircraft, of all warm cloud in the locality, both raingiving as well as non-raining. Provisionally, on basis of general observations made from ground, we may take that no more than 20 per cent occasions of warm cloud development are associated with precipitation release.

We have not considered, so far, possible effects of 'warm' seeding on yield of rain from cold convective clouds (type b). As discussed already, rain development in such clouds is apparently controlled partly by coalescence growth of cloud droplets in their lower layers, and partly by interaction of ice and water phase in supercooled layers above, their relative contributions to raindrop growth varying according to circumstances. In some of these clouds at least, particularly those building up to only a kilometer or two above 0°C level, seeding by warm techniques may, by facilitating the first of the two mechanisms, aid partly or accelerate the process of rain. Further, by quickening coalescence growth of droplets, warm cloud nucleation may help some of the growing drops to reach lower supercooled layers in such sizes that they might freeze spontaneously without freezing nuclei aid (Bigg 1953). Rain initiation by the second, namely, ice mechanism, may also thus be facilitated to a certain extent by such acts of cloud seeding In the absence of a clearer knowledge in regard to relative part played by the two growth mechanisms, it is difficult to estimate the possible effects of warm seeding on rain yield from type-b clouds. Considering that complete failure of rain from supercooled convective clouds during monsoon season is rare, it is felt that the utilities of such seeding from the point of view only of rain initiation may not be great in b-type clouds.

Besides helping some of the clouds to give rain which might not have precipitated otherwise, one may think of certain other possible ways, such as (*i*) causing cloud to start giving rain earlier than normally, (*ii*) increasing efficiency of precipitation process and (*iii*) aiding the cloud treated to gain further in its vertical development, by which seeding operations in an area might bring about some increase in yield of rainfall. As discussed by Roy (1959b), the extent to which cloud seeding might prove fruitful in these various ways in different cloud situations is not easily determinable and is still largely a matter of speculation. Pending further and fuller studies as to how far modification in micro-physical features in a cloud may interact on some of its micro-meteorological conditions, it is difficult to estimate the possible influence of these factors in augmenting rainfall by seeding techniques.

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TABLE 1(a)

Height distribution of rain cells (Monsoon season, 1958)

Date	Height of echo top (km)									Class of day	Remarks
	<4	4-5	5-6	6-7	7-8	8-9	9-10	10-12	>12		
1958 Jul 21	1	1	2	1	6	8	5	—	—	A	Neutral
23	—	—	—	—	—	—	—	2	6	A	No radiosonde
25	—	—	—	—	2	—	—	—	—	A	Do.
26	8	1	—	2	4	—	1	1	—	A	Neutral
29	—	7	2	—	1	—	1	1	—	B	Slight latent instability
30	—	—	—	—	—	2	—	1	—	A	No radiosonde
31	—	—	—	—	2	—	1	1	—	A	Do.
Aug 4	—	—	1	—	2	2	3	4	2	A	Saturated at all heights with lapse rate equal to saturated adiabatic
6	1	—	2	1	5	1	—	1	—	A	Do.
9	—	1	—	—	3	—	1	—	—	A	Neutral
11	—	—	—	1	—	—	2	—	—	A	Very slight latent instability
20	—	—	—	—	—	1	—	1	—	B	Moderate instability
Sep 2	1	5	3	—	—	—	—	—	—	C	Slight to moderate instability
4	9	9	3	1	—	—	1	1	3	B	Stable
5	5	3	—	—	—	—	—	—	—	C	Do.
8	—	2	—	—	—	—	2	—	1	A	Neutral
9	—	—	—	—	3	—	—	—	2	A	Stable
10	—	—	—	3	2	—	3	—	1	A	Slight instability
11	—	2	—	2	2	1	1	3	—	B	Do.
12	—	—	—	1	1	—	—	—	—	B	Slight to moderate instability
18	—	1	1	—	—	—	—	—	—	C	Moderate instability
27	1	1	1	3	1	1	—	—	—	B	Slight instability
29	—	—	—	—	2	—	—	—	—	A	Stable

TABLE 1(b)

Height distribution of rain cells (Monsoon season, 1959)

Date	Height to echo top (km)									Class of day	Remarks
	<4	4-5	5-6	6-7	7-8	8-9	9-10	10-12	>12		
1959 July 2	3	1	—	—	—	—	—	—	—	C	Very slight instability
3	—	1	1	2	—	2	—	1	—	B	Moderate instability
4	—	3	—	—	4	—	1	—	—	B	Do.
6	1	2	1	4	1	1	—	—	2	B	Slight to moderate instability
7	1	—	—	1	—	2	1	1	3	A	Neutral
8	—	2	—	—	—	—	—	—	—	C	Slight instability
9	—	—	2	2	—	—	—	—	—	B	Slight to moderate instability
10	—	—	2	1	—	—	—	—	—	B	Slight instability
13	5	5	—	—	—	—	—	—	—	C	Do.
14	1	2	1	—	1	—	—	—	—	B	Do.

TABLE 1(b)—*contd*

Date	Height of echo top (km)									Class of day	Remarks
	<4	4-5	5-6	6-7	7-8	8-9	9-10	10-12	>12		
Jul 16	—	1	1	—	—	—	—	—	—	C	Very slight instability
18	—	—	2	—	—	—	2	2	—	A	Neutral
20	—	—	3	1	2	—	—	2	1	B	Slight instability
21	—	2	—	2	2	1	—	1	—	B	Slight to moderate instability
22	1	—	1	1	—	3	—	1	—	B	Slight instability
23	1	3	—	—	—	—	—	—	—	C	Slight or no instability
24	3	1	1	—	1	1	1	—	—	B	Slight instability
25	—	—	—	2	1	—	—	1	—	B	Moderate instability
27	—	1	2	2	1	1	—	1	2	B	Slight instability in lower shallow layer
28	1	1	1	—	—	—	—	—	—	C	Very slight or no instability
29	2	2	1	—	—	—	—	—	—	C	No instability
30	2	5	—	—	—	—	—	—	—	C	Morning no instability but afternoon moderate
31	—	1	3	2	8	1	—	—	1	B	Moderate instability
Aug 1	—	—	—	—	4	2	1	—	1	A	Neutral or slight instability
2	—	—	—	—	—	1	—	—	—	A	Saturated at all levels and lapse rate moist adiabatic
3	—	1	3	—	—	2	1	1	1	B	No instability
4	—	—	2	—	3	—	—	—	—	A	Very slight instability
5	—	—	—	1	2	3	—	—	5	A	No or slight instability
6	2	3	2	—	—	—	—	—	—	C	Slight instability
7	—	4	2	2	—	—	—	1	3	B	No instability
8	—	—	—	1	—	—	—	—	1	B	Slight to moderate instability
10	4	2	—	—	—	—	—	—	—	C	Slight instability
11	1	2	—	—	—	—	—	—	—	C	Do.
13	—	—	—	—	1	—	3	1	2	A	No instability
14	—	—	—	—	3	4	1	—	2	B	Slight instability
17	—	1	4	—	—	—	—	—	—	C	Very slight instability
18	—	2	—	2	—	—	—	—	—	B	Slight instability
19	—	1	—	—	—	—	—	—	—	A	Neutral
21	—	—	—	1	—	—	1	—	1	B	No instability
22	—	—	—	1	1	—	—	—	—	B	Slight instability
25	1	—	—	2	3	—	—	2	—	B	Slight to moderate instability
28	—	1	—	—	—	1	—	1	—	B	Slight instability
Sep 1	1	—	—	1	—	—	—	—	—	B	Very slight instability
2	—	1	—	—	—	—	—	—	—	C	Moderate instability
3	—	1	1	—	1	—	—	—	4	B	Do.
4	—	—	2	1	—	—	1	—	—	B	Slight instability
5	—	—	—	—	—	1	—	—	—	B	Do.
6	—	—	—	—	—	1	—	—	4	A	Morning moderate instability but afternoon nil
8	—	2	1	—	1	—	2	—	—	B	Slight instability
9	—	—	—	—	—	—	2	—	—	A	Saturated at all levels following moist adiabatic
12	—	3	1	—	—	—	—	—	—	C	Nil or very slight instability
17	2	2	—	—	—	—	—	—	—	C	Slight instability
22	1	2	1	—	—	—	—	—	—	C	Morning nil afternoon slight
23	1	—	2	3	3	2	2	2	—	B	Morning slight afternoon nil
28	—	—	3	1	—	—	—	1	2	B	Moderate instability in fairly deep layer
29	—	—	—	—	—	—	—	1	2	B	Moderate instability

TABLE 1(c)

Height distribution of rain cells (Winter 1958-59)

Date	Height of echo top (km)									Class of day
	3·5	3·5-5	5-6	6-7	7-8	8-9	9-10	10-12	>12	
1958										
Nov 28	—	2	1	—	1	—	—	—	—	A
Dec 21	—	2	5	—	—	—	—	—	—	A
22	2	2	—	—	—	—	—	—	—	B
26	—	2	—	—	—	—	—	—	—	A
27	—	3	1	5	—	—	—	—	—	B
1959										
Jan 16	—	1	2	3	2	—	—	—	—	B
19	—	—	4	2	5	—	—	—	—	B
20	2	1	3	3	—	—	—	—	—	B
21	—	2	—	3	1	—	—	—	—	B
28	—	6	1	—	2	—	—	—	—	A
Feb 3	—	3	3	—	—	—	—	—	—	A
4	—	1	1	1	—	—	—	—	—	B
18	—	2	—	—	—	—	—	—	—	A

TABLE 1(d)

Height distribution of rain cells (Summer seasons 1958 and 1959 combined)

Date	Height of echo top (km)									Class of day
	<4	4-5	5-6	6-7	7-8	8-9	9-10	10-12	>12	
1958										
Jun 5	—	—	—	—	—	—	1	—	—	B
11	1	3	3	2	3	8	2	2	—	B
12	—	3	—	3	6	—	—	—	—	B
13	1	2	3	3	4	1	1	—	—	B
17	—	—	1	2	—	—	—	3	—	B
18	—	—	—	2	—	—	—	—	—	B
21	—	—	—	1	—	—	—	—	—	B
23	—	—	—	—	—	—	1	1	2	B
1959										
May 27	—	1	2	7	3	2	—	—	—	B
28	1	1	—	3	3	—	—	—	—	B
Jun 3	—	—	—	—	1	—	1	1	1	B
11	—	—	—	—	2	1	—	—	—	B
12	—	—	—	—	1	—	2	—	—	B
13	—	—	3	—	—	—	—	—	—	B
15	—	—	—	—	1	—	—	—	—	B
25	—	—	2	2	—	—	—	—	—	B
26	—	—	—	1	—	—	—	—	—	B

TABLE 2

Height distribution of echo tops relative to rain cells in different seasons

Height of echo top (km)	Monsoon 1958	Monsoon 1959	Summer 1958 and 1959 (combined)	Winter 1958-59
<4	26	33	3	*4
4-5	33	61	10	**28
5-6	15	36	14	21
6-7	15	36	26	17
7-8	36	44	24	11
8-9	16	29	12	1
9-10	21	19	8	—
10-12	16	20	7	—
<12	15	37	3	—

*< 3·5 km **3·5 - 5 km

TABLE 3

Frequency of occurrence of a, b and c-type rain cells in different seasons

Class of day	Number of days	Number of cells of type a	b	c
		MONSOON SEASON 1958		
A	14	52	40	20
B	6	—	27	35
C	3	—	—	19
		MONSOON SEASON 1959		
A	10	31	20	6
B	30	—	134	64
C	16	—	—	70
		WINTER 1958-59		
A	6	16	14	—
B	7	—	48	4
C	—	—	—	—
		SUMMER 1958		
A	—	—	—	—
B	8	—	48	17
C	—	—	—	—
		SUMMER 1959		
A	—	—	—	—
B	9	—	32	10
C	—	—	—	—

TABLE 4(a)

Mean rainfall rates from clouds of the three types in different seasons

Type of cell	Monsoon			Summer			Winter		
a	(4)	2·0	(3·0)		—		(3)	1·6	(2·9)
b	(4)	6·5	(7·2)	(7)	9·0	(17·0)	(5)	8·5	(16·7)
c	(4)	1·3	(1·6)	(4)	1·0	(1·7)	(4)	0·5	(0·8)

NOTE—Figures within brackets to the left give number of rain occasions studied, and those to the right the maximum mean rate observed

TABLE 4(b)

Rainfall rates at successive intervals during life period of a few convective rain cells of 'type-b'

Date	Time (IST)	Distance of rain cells from station (km)	Vertical extension (km)	Estimated rain intensity (mm/hr)	Average intensity (mm/hr)	Duration (mts)
1959						
Aug 7	1049	65	1·4–4·3	0·5		
	1054	65	0–5·5	1·0		
	1057	65	0–6·7	3·7		
	1059	65	0–6·9	>10·5		
	1102	65	0–6·9	>10·5	5·0	>31
	1112	62	0–5·2	6·5		
	1114	62	0–4·1	1·4		
	1116	62	0–3·5	0·8		
	1118	62	0–2·6	0·5		
	1120	62	0·8–2·5	0·3		
Aug 22	1103	85	0–6·2	3·4		
	1105	85	0–7·0	6·1		
	1108	85	0–7·7	>16·7		
	1112	85	0–7·5	>16·7	6·8	>43
	1114	83	0–7·0	>16·7		
	1116	83	0–6·5	>16·7		
	1123	83	0–7·3	4·1		
	1133	81	0–7·0	2·0		
	1143	81	1–5·5	0·2		
Aug 25	1428	92	1–4·7	0·8		
	1432	92	0–5·9	3·0		
	1434	93	0–6·6	6·1	7·2	>19
	1440	93	0–6·3	16·7		
	1443	94	0–4·7	10·2		
	1445	94	0–3·8	0·6		
	1447	94	0–2·3	0·1		
Sep 1	1101	70	0–4·6	0·9		
	1108	70	0–5·8	6·3		
	1115	72	0–6·3	1·8		
	1134	75	0–5·0	3·0		
	1137	78	0–5·7	6·5		
	1140	78	0–6·0	8·6		
	1144	78	0–5·3	1·7		
	1152	78	0–5·4	6·0	7·2	>129
	1200	78	0–5·7	6·3		
	1202	78	0–6·1	10·4		
	1205	78	0–6·6	10·4		
	1209	78	0–7·5	3·0		
	1215	78	0–6·6	12·6		
	1220	80	0–6·2	11·4		
	1235	80	0–5·4	12·6		
	1239	80	0–6·7	12·6		
	1247	80	0–7·5	4·5		
	1255	80	0–6·6	0·7		
	1258	80	0–5·6	0·5		
	1305	80	0–4·9	0·7		
	1308	80	0–4·0	0·3		
	1310	80	0·2–3·2	0·1		

TABLE 4(c)

Rainfall rates at successive intervals during life period of a few convective rain cells of 'type-c'

Date	Time (IST)	Distance of rain cells from station (km)	Vertical extension (km)	Estimated rain intensity (mm/hr)	Average intensity (mm/hr)	Duration (mts)
1959						
Jul 28	1150	45	0·5–4·5	0·8		
	1153	45	0–4·5	1·7		
	1155	45	0–4·5	0·6	0·73	>11
	1201	45	0·5–3·7	0·03		
Jul 30	1532	17	0–4·8	0·4		
	1536	18	0–4·8	>2·0		
	1541	19	0–4·8	>2·0		
	1545	20	0–4·2	>2·0		
	1549	20	0–3·8	2·0	1·4	>26
	1552	21	0–3·8	0·7		
	1556	22	0–3·6	0·2		
	1558	23	0–3·3	0·1		
Aug 11	1425	43	1·0–4·2	0·3		
	1428	43	1–4·4	0·3		
	1431	42	0–4·4	5·3		
	1435	42	0–4·4	1·6	1·6	>20
	1437	41	0–4·3	1·3		
	1441	40	0–3·4	0·8		
	1445	40	0–3·0	0·03		
Aug 17	1453	42	0–3·3	0·6		
	1456	40	0–3·6	2·0		
	1502	40	0–3·6	1·3	1·3	>15
	1507	38	0–3·6	0·6		

TABLE 5

Percentage contributions to season's rainfall by cells of different types

Season	Type of rain cells		
	a	b	c
Summer 1958 and 1959 (combined)	—	99·2	0·8
Monsoon 1958	69·6	29·1	1·3
Monsoon 1959	37·5	60·3	2·2
Monsoon 1958 and 1959 (combined)	52·6	45·6	1·8
Winter 1958-59	32·6	67·3	0·1