Size Distribution of Radar Echoes as an Indicator of Growth Mechanisms in Monsoon Clouds around Madras

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ABSTRACT

A study of the size distribution of radar echoes from precipitating clouds around Madras during the southwest and northeast monsoon seasons shows a preponderance of echo sizes in the D scale (up to 100 km^2) with relatively small percentages in the C scale (101 to 1000 km^2) and in the B/C scale (>1000 km^2). The largest echo size observed was 21 000 km^2. If the cumulative percentage frequencies of areas of cells are plotted on logarithmic probability paper, the smaller cells constituting 85–95% of the total population are seen to follow a lognormal distribution. In the larger size ranges, however, systematic deviations on either side of the lognormal graph occur.

The lognormal distribution points to a growth mechanism of convective cells by a process whereby growth at every step is a random proportion of the initial size. The deviations from the lognormal distribution in the land area in the northeast monsoon season indicate limitation of growth after the cells which develop over the sea drift over the land. In the southwest monsoon season and in the sea area during the northeast monsoon, growth is found to occur to very large sizes more often than a lognormal distribution would predict. The deviation from lognormality appears to be due to development of a stratiform mesoscale anvil cloud similar to the model of Leary and Houze in the Global Atmospheric Research Program's (GARP) Atlantic Tropical Experiment (GATE).

1. Introduction

It is generally accepted that an initial population of small convective cloud elements is produced by large-scale features of the flow and these elements grow further, entraining environmental air in some random proportion of the initial mass. It has been shown by López (1976, 1977) that this process of growth would lead to the frequency distribution of sizes of convective elements being *lognormal.*

The theory of the lognormal distribution will not be discussed here since it can be found in standard references on statistics (e.g., Croxton *et al.*, 1969). If this distribution is applicable, the cumulative percentage frequency of sizes of clouds or their radar echoes plotted on logarithmic probability paper should yield a straight line. López (1977) and Houze and Cheng (1977) have shown that this is generally so (except for very large echoes) in the case of tropical convection in the Americas and in the Atlantic. In addition to the growth of an individual cumulus, clouds can grow by merger into larger elements. According to López (1977), the law of proportionate effects is applicable to small convective elements both because the physics of turbulent entrainment favors the growth of larger elements, and because clouds which have a large initial size may intercept a larger number of elements and growth by merger proceeds according to a law of proportional effects leading to a lognormal distribution.

2. Size distribution of radar echoes around Madras

Does this type of size distribution prevail in the Indian region? If so, does the growth of the initial cumulus continue indefinitely according to the law of random proportions, or do other mechanisms come into play? Utilizing a comprehensive set of radar observations which has become available for the first time because of the Monsoon Experiment 1979 (MONEX), a component of the Global Atmospheric Research Program (GARP), we seek answers to these questions. With the Cyclone Warning Radar[1] at Madras (13°5′N, 80°17′E) hourly observations in the form of photographs have been taken in the years 1977[2] and 1979 both in the southwest and northeast monsoon[3] seasons. Frequency distributions of sizes of radar echoes from convective elements were compiled using only the radar pictures at synoptic hours

[1] Parameters: 10.4 cm wavelength, 500 kW peak power, 4 μs pulse width, 1.9° beamwidth, −110 dBm minimum detectable signal. Radar is close to the coast; antenna is at an elevation of 20 m above sea level. Usual operation was at 0° elevation at a scanning rate of 6 rpm. Analog processing for video integration, range normalization and display of eight isoecho levels at 5 dB(Z) intervals was available up to a range of 200 km. A digital video processor has been added subsequent to the research presented here.

[2] In 1977 a program of observations known as MONSOON-77 was conducted as a precursor to the MONEX.

[3] The period October to December with prevailing northeasterlies bringing appreciable rainfall over the Madras area is locally termed the northeast monsoon.

TABLE 1. Distribution of convective clouds in different size scales.

Season	Total population	Percentage of cells in scale		
		D	C	B/C
(A) Sea area				
SW Monsoon 1979	595	80.2	17.5	2.3
SW Monsoon 1977	715	73.4	21.7	4.9
NE Monsoon 1979	1581	79.7	18.5	1.8
NE Monsoon 1977	1879	78.0	21.2	0.8
(B) Land area				
SW Monsoon 1979	531	81.2	17.3	1.5
SW Monsoon 1977	892	80.3	18.2	1.5
NE Monsoon 1979	986	85.3	14.6	0.1
NE Monsoon 1977	1012	78.5	21.1	0.4

(0000, 0300, 0600, 1200, 1500, 1800, 2100 GMT) so that the sampling interval was appreciably larger than the average life of individual cells. The successive observations were expected to yield independent members of the population. This was not, however,

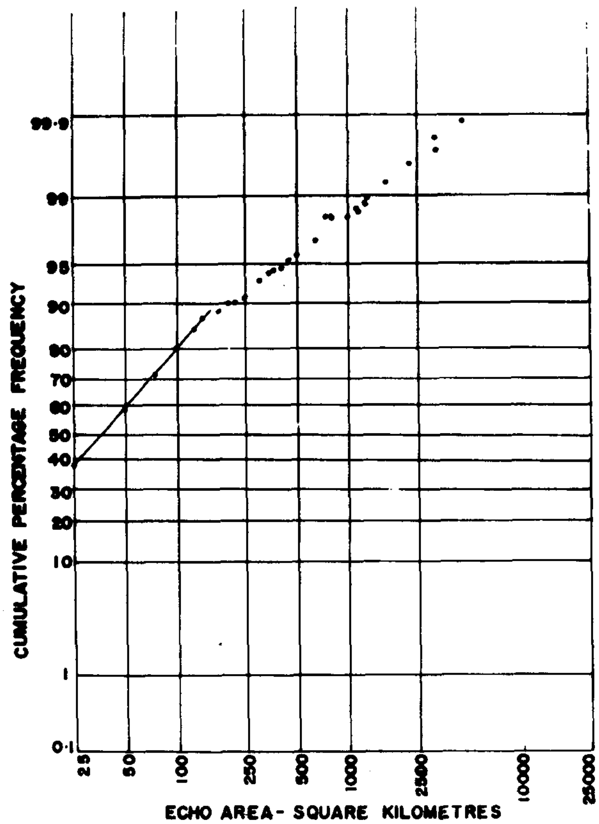

FIG. 1. Frequency distribution of echo sizes, southwest monsoon season 1979, sea area.

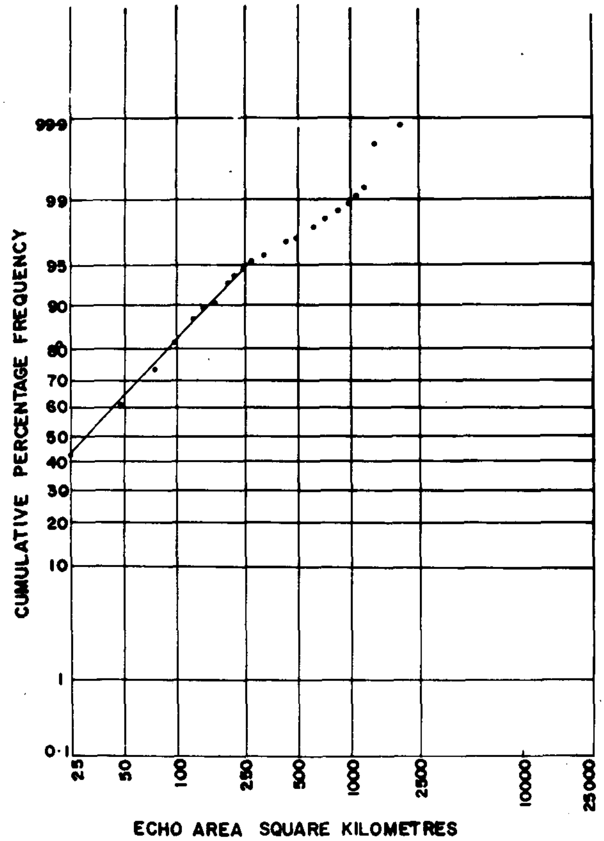

FIG. 2. As in Fig. 1, but for land area.

true of very large echoes which had lifetimes larger than 3 h. Separate statistics for land and sea areas, around Madras were prepared for each season. Following the nomenclature of GATE (GARP Atlantic Tropical Experiment) (e.g., Houze and Cheng, 1977) the population was divided into three scales, *viz.*, D scale ($\leqslant$100 km^2, generally associated with pure convection), C scale (101–1000 km^2) and B/C scale ($>$1000 km^2). The latter two are generally considered "mesoscale." The distribution is shown in Table 1. It is seen that in both seasons 73–81% of radar echoes are in the D scale, 17–21% in the C scale and the remainder (0.1–5%) in the B/C scale. The latter included echoes up to a size of 21 000 km^2. Note also that the percentage of echoes in the B/C scale over the land area in the northeast monsoon season (last two rows in Table 1) are appreciably lower than in the other cases. The significance of the latter result will be discussed subsequently.

The cumulative percentage frequencies of the various sizes of echoes in each of these seasons are plotted on the Y axis on a probability scale in Figs. 1–6. The X axis is on a logarithmic scale and gives echo area in square kilometers. The areas were measured by superposing a 5 km $\times$ 5 km grid overlay on

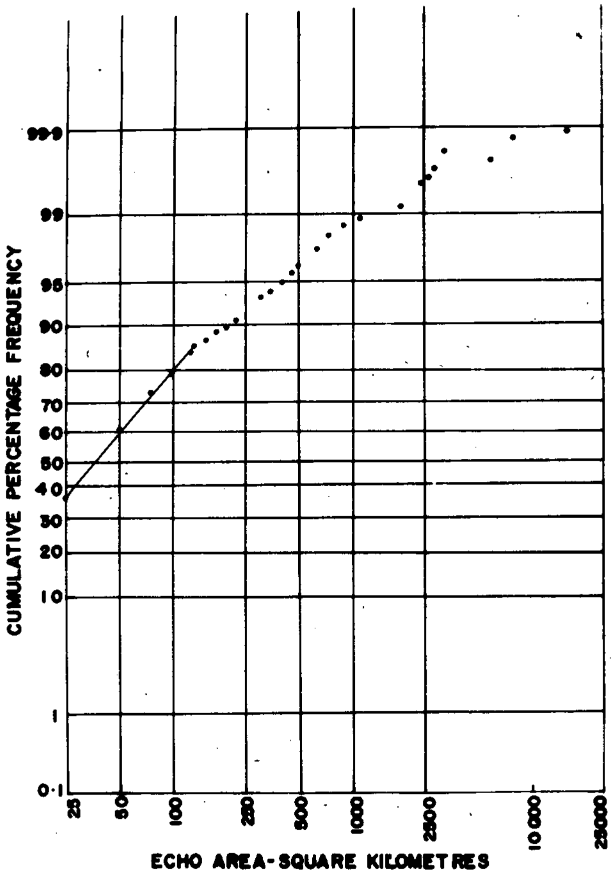

FIG. 3. As in Fig. 1, but for northeast monsoon season 1979, sea area.

projected PPI pictures containing raw video out to a range of 200 km. Since the raw video is not range-normalized, the sizes of distant echoes can be underestimated. However, this is not likely to result in significant bias in the cumulative frequency distribution since the echoes of different sizes are present at all ranges and since the cumulative frequency implies that each echo is included in all the size classes larger than its own (López, 1978). It may be seen that in each of the six cases thus far presented, ~85–95% of the population representing echoes up to ~200 km^2 in size—what may be called the convective scale echoes—obey the lognormal distribution closely. However, echoes larger than a few hundred square kilometers fall *below* the lognormal straight line drawn in Figs. 1–6.

What is the physical significance of this deviation from the lognormal relationship? To understand this, let us consider a distribution truncated to the C scale, i.e., 1000 km^2, by discarding the larger echoes. This is equivalent to assuming that echoes do not grow to the B/C scale. Such a truncated distribution for one of the seasons (southwest monsoon 1977, sea area) is shown in Fig. 7. It will be seen that, as compared with the full series (Fig. 6), the straight line fits better up to 98% of the echoes corresponding to a size limit of 500 km^2. Beyond that, the points lie *above* the line, i.e., if growth is limited—by whatever mechanism—to some low upper limit, the distribution deviates *above* the lognormal line. Conversely, if growth to very large sizes is frequent, the distribution deviates *below* the straight line. Hence, in the six actual cases shown, we may infer that while the lognormal distribution is followed in the D and at least in part of the C scale, very large echoes (of the order of some thousands of square kilometers) are *more* numerous than would be the case if the growth by random proportion had continued. In other words, some new mechanism takes over at mesoscale sizes and the law of random proportion ceases to be valid.

We have thus far seen the frequency distribution for the southwest monsoon season and for the sea area only of the northeast monsoon season. Over land in the northeast monsoon the situation is rather different. As seen from Figs. 8 and 9, the lognormal distribution fits up to a few hundred square kilometers and beyond that, the points lie *above* the line.

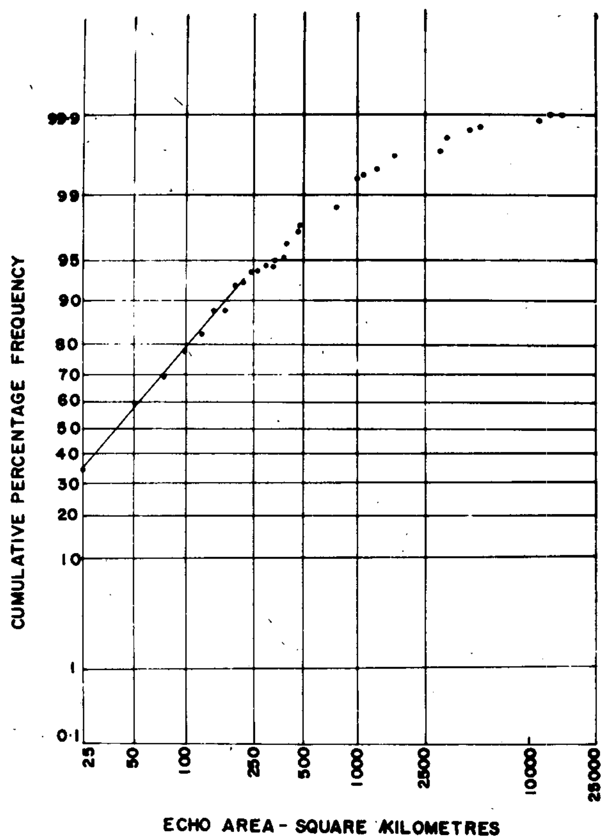

FIG. 4. As in Fig. 1, but for northeast monsoon season 1977, sea area.

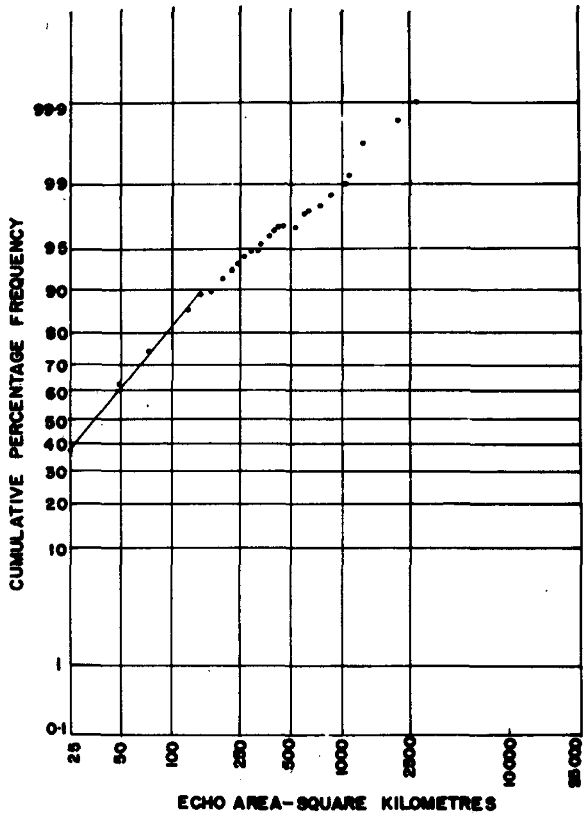

FIG. 5. As in Fig. 1, but for southwest monsoon season 1977, land area.

As discussed earlier, this implies that growth to very large sizes is rare, which was also noted in Table 1.

3. Explanation of deviations from the lognormal

In the Western Hemisphere studies by López (1976, 1977, 1978) and Houze and Cheng (1977), the lognormal distribution was found to fit ~98% of the echoes. The deviation from lognormal beyond that was *above* the line, i.e., very large echoes were fewer than if the distribution were lognormal. This is explained by López (1977) in terms of a physical limit to growth of clouds. During the northeast monsoon, most of the convective development occurs over the sea. The echoes which drift over land produce rain, but do not usually develop further in size or height. The observed distribution of precipitation in the northeast monsoon, i.e., a rapid decrease as one proceeds westward from the coast, is also consistent with this finding. Hence, the observed size distribution over land in the northeast monsoon is explained by growth according to the law of random proportion limited to a size of the order of 1000 km^2.

However, growth of echoes occurs to very large mesoscale sizes in the southwest monsoon season and over sea in the northeast monsoon season (Figs. 1–6). The growth of convective cells into the mesoscale has been studied intensively in the last 15 years in the Western Hemisphere by Riehl (1969), Zipser (1969, 1977), Houze (1977) and Leary and Houze (1979a,b), among others. The general picture developed by these studies is the extension of a large mid- and upper-tropospheric anvil cloud emanating from a well-developed group of convective cells. The anvil of a cumulonimbus is conventionally thought of as inactive cirriform debris blown off from the cumulonimbus top. The concept of these authors, however, is of an extensive and thick (up to 10 km) layer cloud capable of contributing an appreciable amount of horizontally uniform light rain. A model of a mesoscale cloud consisting of active convective cores at the forward edge with a large trailing anvil cloud in the rear was developed by Houze (1977) in his study of a GATE squall line. The convective cores contain large vertical and horizontal gradients of radar reflectivity, while the anvil exhibits a bright band in a well-defined melting layer. Leary and Houze (1979a) extended this model to tropical cloud clusters other than squall lines in the Atlantic. The trailing anvil region is supposed to be characterized by a mesoscale

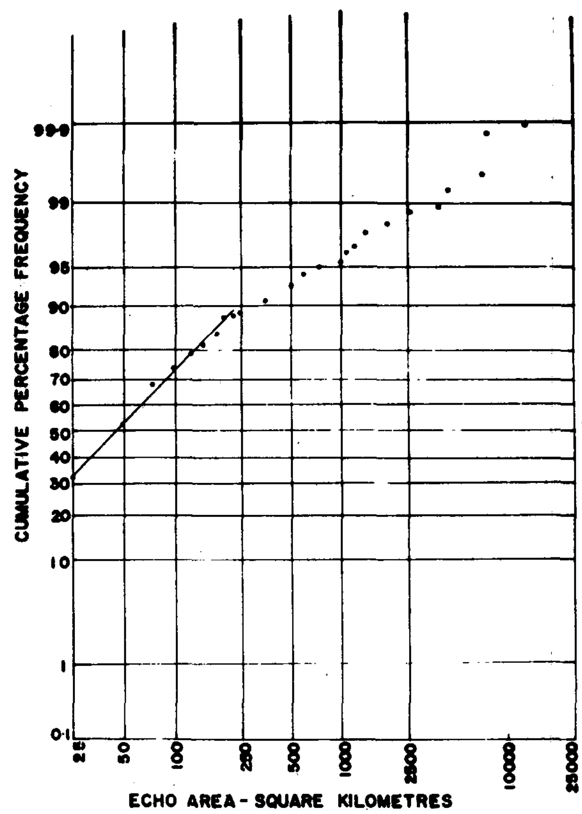

FIG. 6. As in Fig. 1, but for southwest monsoon season 1977, sea area.

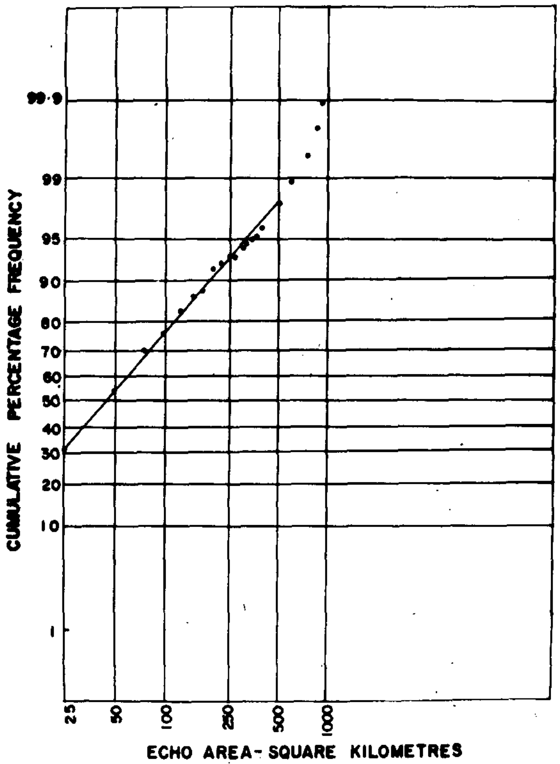

FIG. 7. Frequency distribution of echo sizes truncated to 1000 km^2 by discarding larger echoes, southwest monsoon season 1977, sea area.

unsaturated downdraft of the order of 10 cm s^{-1} (Zipser, 1969, 1977) while convective downdrafts are typically 1–10 m s^{-1}. While the rainfall rate in the anvil cloud (~3 mm h^{-1}) is considerably less than in the convective cores (up to 100 mm h^{-1}), the precipitation contributed by the large anvil area is found by Houze (1977), Cheng and Houze (1979) and Gamache and Houze (1981) to be some 40–50% of the total precipitation. A numerical model for this kind of mesoscale organization has been developed by Brown (1979).

Does convection in the Madras area have a tendency to develop such large precipitating anvil clouds? If so, it would explain the substantial number of B/C scale echoes observed in the southwest monsoon season and over the sea in the northeast monsoon. While the radar data available to us do not permit us to trace the origin or nature of downdrafts, the internal structure of large individual echoes could be examined from PPI and RHI radar isoecho pictures. Fig. 10, for instance, is an isoecho contour diagram from 15 November 1979. It can be seen that there are several convective cores in the echoes over the sea with high reflectivity factors [of the order of 44 dB(Z)] and large horizontal reflectivity gradients. In the large echo which is over the station, the reflectivity is low and nearly uniform. The RHI's show horizontal stratification as inferred from the bright band (Fig. 11). This structure is in direct contrast to the vertically oriented reflectivity contours characteristic of an active convective cloud. The areal precipitation contributed by the echoes at the lowest isoecho level, i.e., the lowest rainfall rate in Fig. 10, is computed to be 49% of the total precipitation. This ratio is consistent with the results of Houze (1977), Cheng and Houze (1979) and Gamache and Houze (1981). This indicates that large stable mesoscale extensions can accompany convective cells, and this type of structure may account for the substantial number of B/C scale echoes and the observed deviation from the lognormal distribution.

Since this extension is apparently not a case of growth by random proportion, the mechanism of this phenomenon can probably be understood by studying the dynamics more intensively and not from the statistics alone. There is, however, one important difference between the model of Leary and Houze (1979a) and our mesoscale cloud shown in Fig. 10. In the cases studied by them, the anvil is always considered as a trailing cloud behind the convective core. They explain this as due to the low-level winds being

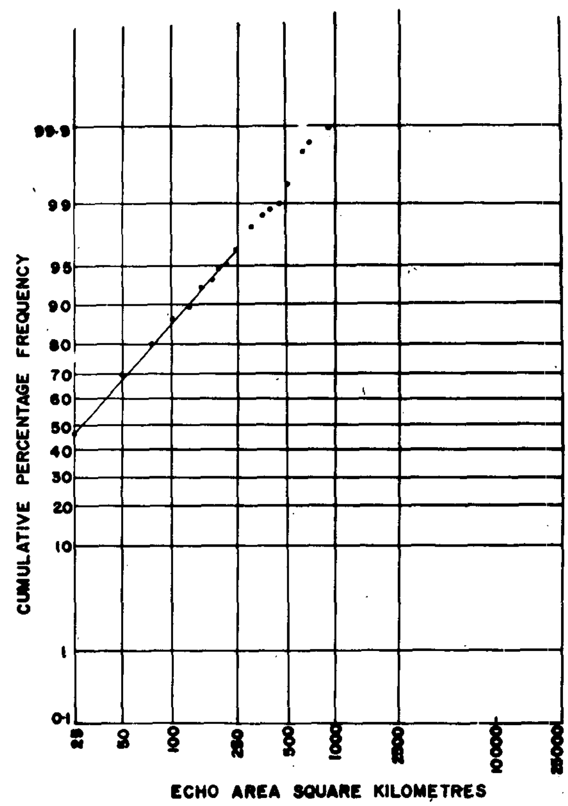

FIG. 8. Frequency distribution of echo sizes, northeast monsoon season 1979, land area.

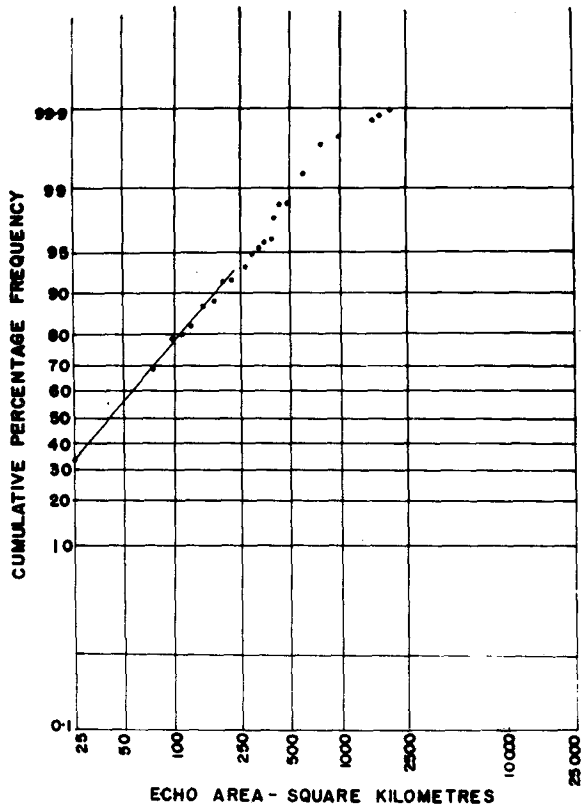

FIG. 9. As in Fig. 8, but for 1977, land area.

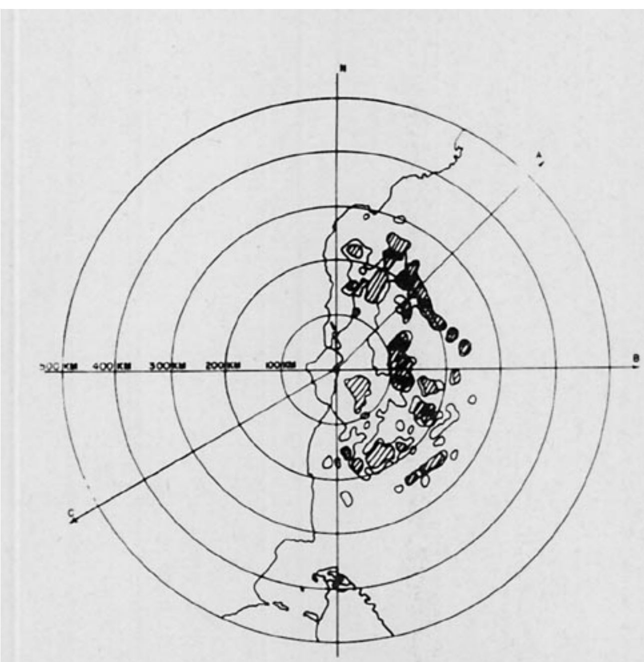

FIG. 10. Tracing of radar picture 500 km around Madras, 15 November 1979, 1039 Indian Standard Time. Normal echo above a threshold of ~20 dB(Z) shown as outline. Hatched area is echo above a threshold of 34 dB(Z). Black area is echo above threshold of 44 dB(Z). Bright band was observed up to 50 km range in directions A, B, C in the stratiform echo.

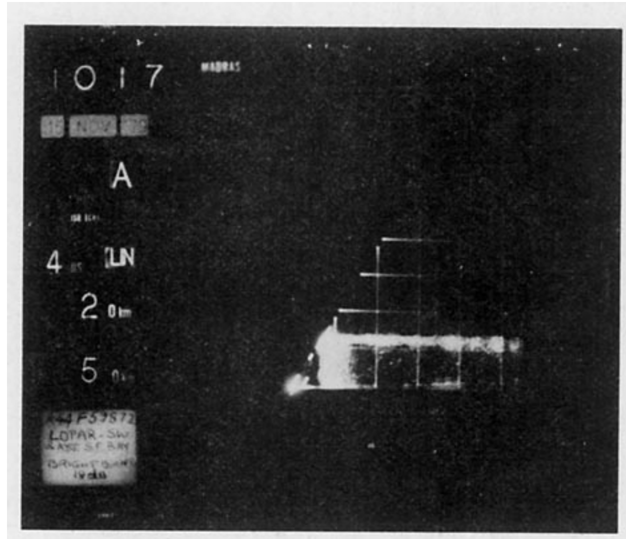

FIG. 11. Range Height Indicator photograph exhibiting bright band. Range and height markers are at intervals of 10 and 5 km respectively. Receiver attenuation setting is 18 dB.

opposite to the direction of motion of the convective clouds. This results in further convection occurring preferentially at the leading edge, while the dissipating elements join the trailing anvil cloud where intense convection is discouraged by the mesoscale downdraft. This kind of wind regime does not apply to our area. The low-level winds on 15 November 1979 were, for example, easterly, while the midtropospheric winds which probably determined the motion of the cells were also easterly. Hence, the observed mesoscale stratiform cloud was not a trailing cloud. In a recent study of winter monsoon convection in the vicinity of North Borneo, Houze *et al.* (1981) have found that the mesoscale stratiform anvil cloud occurs in that region also, but not as a trailing cloud.

4. Summary and conclusion

The observed statistical distribution of sizes of radar echoes indicates a preponderance of small sizes and growth according to a law of random proportions up to a size of a few hundred square kilometers. Further growth beyond this size does not appear to occur to any significant extent over land in the northeast monsoon season. However, over sea in that season and over both land and sea in the southwest monsoon season growth occurs well into sizes of several thousand square kilometers, and the frequency of such large echoes is more than would be expected by growth according to the law of random proportions. The larger sizes are probably accounted for by the development of a large mesoscale anvil cloud as an extension of the convective cell but different in internal structure.

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REFERENCES

Brown, J. M., 1979: Mesoscale unsaturated downdrafts driven by rainfall evaporation: A numerical study. *J. Atmos. Sci.*, **36,** 313–338.

Cheng, C.-P., and R. A. Houze, Jr., 1979: The distribution of convective and mesoscale precipitation in GATE radar echo patterns. *Mon. Wea. Rev.*, **107,** 1370–1381.

Croxton, F. E., D. J. Cowden and S. Klein, 1969: *Applied General Statistics.* Prentice-Hall of India, 754 pp.

Gamache, J. F., and R. A. Houze, Jr., 1981: The water budget of a tropical squall-line system. *Preprints 20th Conf. on Radar Meteorology*, Boston, Amer. Meteor. Soc., 346–352.

Houze, R. A., Jr., 1977: Structure and dynamics of a tropical squall-line system. *Mon. Wea. Rev.,* **105,** 1540–1567.

——, and Chee-Pong Cheng, 1977: Radar characteristics of tropical convection observed during GATE: Mean properties and trends over the summer season. *Mon. Wea. Rev.*, **105,** 964–980.

——, S. G. Geotis, F. D. Marks and A. K. West, 1981: Winter monsoon convection in the vicinity of North Borneo. Part I: Structure and time variation of the clouds and precipitation. *Mon. Wea. Rev.*, **109,** 1595–1614.

Leary, C. A., and R. A. Houze, Jr., 1979a: The structure and evolution of convection in a tropical cloud cluster. *J. Atmos. Sci.*, **36,** 437–457.

——, and ——, 1979b: Melting and evaporation of hydrometeors in precipitation from the anvil clouds of deep tropical convection. *J. Atmos. Sci.*, **36,** 669–679.

López, R. E., 1976: Radar characteristics of the cloud populations of tropical disturbances in the North Atlantic. *Mon. Wea. Rev.*, **104,** 268–283.

——, 1977: The lognormal distribution and cumulus cloud populations. *Mon. Wea. Rev.*, **105,** 865–872.

——, 1978: Internal structure and development processes of C scale aggregates of cumulus clouds. *Mon. Wea. Rev.*, **106,** 1488–1494.

Riehl, H., 1969: Some aspects of cumulonimbus convection in relation to tropical weather disturbances. *Bull. Amer. Meteor. Soc.*, **50,** 587–595.

Zipser, E. J., 1969: The role of organized unsaturated convective downdrafts in the structure and rapid decay of an equatorial disturbance. *J. Appl. Meteor.*, **8,** 799–814.

——, 1977: Mesoscale and convective scale downdrafts as distinct components of squall-line structure. *Mon. Wea. Rev.*, **105,** 1568–1589.