

Reply

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The major points of my paper are that the initial development of rain in cumulus clouds of our area is strongly dominated by the coalescence mechanism and that ice particles develop in virtually every cloud which reaches a temperature of -10°C *provided* that it had previously developed warm rain.

If I correctly understand the question raised by Howell, he asks whether the clouds that are the concern of our study account for any appreciable fraction of the summer rainfall. This is an important question and one to which I gladly respond. In this instance the question was raised in the contest of cloud seeding. Our data speak directly to that point since the basic cloud studies were part of a five-year randomized cloud seeding experiment. However, analysis of the latter is still in progress and will be the subject of a major report in the near future. For the present reply I will draw upon certain *preliminary* statistics from the seeding study and other unpublished basic cloud studies. Complete statistics then will be offered for publication as soon as the analyses are complete.

The basic concern of Project Whitetop was all of the clouds of any type, size and degree of vigor, that developed precipitation anywhere within an area 120 miles diameter, centered at West Plains, Missouri, during a certain set of afternoons of June, July and August. Clouds and rain that occurred during the morning hours were not the concern of the study. Operational afternoons were selected on the basis of a set of "prediction criteria" developed prior to the experiment. In the five summers of the study (1960-1964 incl.) a total of 198

afternoons were selected for operations. On each of these the ground based radar was operated, with scope photography regardless of the number and kinds of echoes present, continuously from about noon until late evening (1200-2400 LST in 1960,61; 1100-2100 LST in 1962,63,64). Radar echoes were observed and photographed on 182 of the 198 afternoons. The average total rainfall in our area for the five summers combined was about 36 inches. Of this, a total of about 21 inches occurred during operational hours (defined above) on all summer days both operational and non-operational. On the particular 198 afternoons selected for operations the area experienced a total of about 15 inches of rain. Thus periods of Project Whitetop operational afternoons represent about 40 per cent of the *total* summer rainfall, and about 75 per cent of the afternoon rainfall. Our basic radar data represents a significant fraction of the total summer rainfall and the majority of all afternoon rainfall. Although the seeding project was set up on the basis of the convective rain processes, *all* of the radar data are being used along with raingage data in the analysis of the seeding effect.

Radar data from only the first three summers were used in the first-echo analysis, from which came the strongest evidence for the importance of coalescence in the development of rain in cumuli of that area. In this analysis we had to restrict ourselves to days of convective echoes and convective rain. Deleting the days of stratified weather only slightly reduced the number of days of data but had the effect of deleting many of the days of greatest average rain. For example, in 1960 we

had 43 operational days, 38 of which gave echoes. Five of these days had stratified cloud conditions which we could not include in the first-echo analysis. On the 33 convective echo days over 6,000 individual echoes were identified; of these about 2,700 were regarded to be valid first echoes in that the echo formed within the radar area and far enough from other echoes to be clearly identifiable as a new echo. From the first three summers we had over 7,200 valid first echoes which constituted a 100-per cent sample of clearly identifiable first echoes from about 658 hours of convective activity. The rainfall during these hours bulked about 25 per cent of *all* summer afternoon rainfall, but it obviously was not limited to the rain from the particular 7,200 echoes for which valid initial conditions were observable.

This first-echo analysis shows that about 90 per cent of the new echoes formed at such low heights that the echo producing particles certainly were liquid. The other 10 per cent might have been caused by ice particles. There seems to be a tendency for the higher and colder first echoes to be associated with the more vigorously growing clouds, but this point has not been thoroughly studied.

The fact that the initial precipitation particles are liquid would not, of itself, negate the possibility that seeding with ice nuclei might release the heat of fusion and cause additional cloud growth as described by Malkus and Simpson (1964). Analysis of our in-cloud samples of hydrometeors, collected from the instrumented airplane, makes me feel that it is unlikely that this would occur very often in clouds which have already developed precipitation. The reason is that even though the clouds first develop precipitation via the coalescence mechanism they very quickly become filled with ice particles as soon as the top reaches a temperature of about -10C (Koenig, 1963). These ice particles appear to have come from freezing of the large drops, but the number of ice particles usually is much larger than the number of warm-rain drops that preceded them. Moreover, the ice first appears at temperatures much warmer than I would expect from any of the ice nuclei measurements of which I am aware.

The airplane measurements were made routinely on all days of convection, both operational and non-operational. Our preferred flight level was about -10C ; it was seldom higher because of airplane limitations, it was frequently lower because nature provided many days in which few clouds grew above the -10C level. The flight data are biased toward the more vigorously growing clouds because only these last long enough for effective sampling. It is completely incorrect to assume that the airplane measurements represent the same class of clouds sorted out for the first echo study. Although this point may not have been clearly stated in my paper (and I am grateful for this opportunity for making it clear), it was covered more thoroughly in the original papers to which I referred. For example, as Koenig points out,

the average lifetimes of clouds studied with the airplane was of the "order of an hour."

As far as I am aware the major deficiency in our airplane data is that they do not contain a representative sample of the truly giant thunderstorms or "severe storms." Such storms are relatively infrequent in summer-time Missouri and we made no effort to systematically sample them. For one reason our maximum useful ceiling of about 20,000 ft is so far below the tops of these clouds that no useful description of them could be obtained. On the other hand, we made no particular effort to avoid these storms. To obtain the samples of large snow pellets needed for density and falling speed measurements it was necessary to make collections in some of the largest clouds of the summer. For example in the flights we have recorded updrafts of over 6,000 ft per minute, and on the flight of 11 August 1964 hail about $1\frac{1}{2}$ inch diameter resulted in such extensive damage that the plane was grounded for three days for repair of airfoil leading edges and fiberglass mountings.

At the other end of the size spectrum are the small cumuli which reached top heights of -5C to -15C without developing precipitation of any kind. Obviously these are not included in the echo analyses. Our flight measurements contain many examples of this type cloud. Typically they had very short life spans—of a matter of minutes above the freezing level. To what extent these clouds could be given new vigor by the Malkus-Simpson "massive overseeding" approach is unknown, but obviously worthy of study.

Let us turn now to the direct question raised by Howell. The figure of nine minutes duration refers to the period of rain at the ground from a sample of 928 echoes that were selected from the 1960 data as being convective echoes of the simplest kind. In terms of first echo heights these simple echoes gave values similar to those obtained in the analysis of 7,200 first echoes. *But* these simple echoes are not to be viewed as typical of the clouds sampled by the airplane. In fact for any discussion of the findings of the occurrence of natural ice particles, the question of the amount of rain from these simple echoes is largely irrelevant.

It is an important meteorological question, however, to know the amount of rain that falls from cumuli of various sizes and amounts of growth. To my knowledge there has never been a careful study of the rain from individual convective echoes. I agree that the majority of convective rain comes from relatively few clouds of considerable vigor. To put this into completely quantitative language is impossible but perhaps we can make an estimate by using the simple convective echo study mentioned in the early part of my paper.

Fifteen of the 33 afternoons of convective cloud conditions in 1960 were selected for what we call a "complete life history" analysis. In this study we kept track of the size and location of each echo throughout its individual life time. These 15 days gave about 4400 indi-

vidual convective echoes of which 928 were simple, single cell, echoes for which we had a complete life history. This excluded all echoes that moved into the radar area, moved from the area, had interrupted records because of equipment malfunction or film change or were of a complex nature.

The rainfall on these 15 days was about average for the summer. The total summer rainfall was a little under nine inches (all hours, all days). About five inches fell during the afternoon hours, of which about four inches, i.e., about 80 per cent, fell on operational afternoons. Almost two inches of this fell on the five days with stratus clouds, leaving a total of only two inches for the 38 convective weather afternoons. A little over one inch of this fell on the 15 afternoons selected for complete analysis.

If we accept this subsample of echoes as representative of all convective echoes we can estimate the relative rainfall contribution of echoes of different sizes by the following analysis. For each echo we have both horizontal and vertical dimensions as a function of time. We assume that each echo has a circular cross section with a diameter equal to its maximum horizontal dimension at the time it reaches its maximum height. By multiplying this area by the observed duration of rain to the ground from that echo we arrive at an area-time product which should be equal to the total amount of rain

from the echo divided by its average intensity. Considering now only those echoes which rained to ground from the 1960 simple echo study, we find that 564 simple cumulus echoes which grew 5,000 ft or less had an aggregate area-time product of 110.6 mi² hr, while 35 echoes which grew more than 5,000 ft had an area-time product of 45.0 mi² hr (almost equally divided between echoes growing 6-10,000 ft and those growing more than 10,000 ft). *If* the rainfall intensity, averaged over time and area, from the fewer but more vigorous clouds was between two and three times that of the more numerous but less vigorous clouds, the two groups would contribute about equally to the total rainfall. Actually the average rain intensity from the more vigorous group of clouds probably is more than three times that of the less vigorous group, but probably not 10 times as large. Thus we deduce that simple convective echoes growing more than 5,000 ft contribute two to five times as much rain as the simple convective echoes which grow less than 5,000 ft.

I hesitate to extend this to an estimate of the total rain at the ground from echoes of various kinds because the sample of "simple" echoes is small and was selected on the basis of echo simplicity. In any event it seems to me that this aspect of Howell's correspondence is only peripherally related to the main points of my paper.