Some Factors Governing Precipitation and Lightning from Convective Clouds

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ABSTRACT

Two groups of days, one with "heavy rain" and one with "light rain," have been studied. Radar observations, cloud photographs and visual counts of cloud-to-ground lightning were examined. It is concluded that, at least in convective clouds in southeastern Arizona and probably in convective clouds in other geographical regions as well, the microphysical properties of the clouds are not of dominant importance in determining how much precipitation reaches the ground. It is inferred that the quantity of rainfall is mostly governed by those properties of the atmosphere which determine the size, strength and duration of the updrafts. The observations also show that as the quantity of rainfall increases so does the frequency of cloud-to-ground lightning.

1. Introduction

Most cloud modification studies aimed at increasing rainfall are based on the assumption that, in the atmosphere, there is a deficiency of specific types of nuclei. Convective clouds in low latitude maritime regions have been seeded with giant salt nuclei or sprays of water droplets. Supercooled convective clouds have been seeded with ice nuclei. The physical argument for taking these steps is that the deficiency of nuclei does not allow the so-called "precipitation efficiency" of a cloud to reach its optimum level. For example, see Elliott (1958). This argument implies that the microphysical properties of the cloud are the important, in some cases the dominant, factors governing the quantity of precipitation.

Starting during the summer of 1957, an extended series of experiments involving the seeding of convective clouds with silver-iodide nuclei have been conducted in southeastern Arizona. The design of the tests has been described by Battan and Kassander (1960). These experiments have not succeeded in showing that silver-iodide nuclei significantly modified the quantity or distribution of precipitation or the vertical extent of the radar echoes produced by the clouds. The initial four years of testing were not sufficient to draw a conclusion that silver-iodide seeding has no effect, but the results were certainly discouraging. Two additional years of testing have not supplied information any more encouraging than was obtained in the first set of experiments.

It is important to learn why it was not possible to show that silver-iodide seeding modified the rainfall by a measurable amount. One possibility is that the initial conception of the role of ice nuclei in convective precipitation was not correct. Perhaps in convective clouds of the type normally found in southeastern Arizona in the summer, ice nuclei are of secondary importance in the rainfall process. This paper is concerned with examining this point in some detail.

2. Rainfall observations

During the summers of 1957 through 1960, precipitation measurements were made over the Santa Catalina Mountains by means of 29 recording gages distributed in the manner shown in Fig. 1. They had an average spacing of 7 km and covered an area of about 1,000 km². In 1961 and 1962, the number of gages was increased to 35 and concentrated over the higher terrain. The total area covered was reduced to about 800 km².

As was to be expected from the nature of convective rains, there was considerable variation in rainfall amounts from one day to the next. A question of prime importance is, "What is the difference between days with heavy rain and days with light rain?"

During the six summer periods, 1957 to 1962, rainy days were classified in accordance with a scheme depending on how much rain was measured during the period 1300 to 1800 MST. This period, which includes most of the heavy rainfall over the mountains, was the same one used for evaluating the effects of the cloud seeding.

Mean rainfall per day per gage, $\bar{R}$, was used to classify each day. When $\bar{R}$ exceeded 0.10 inch, the day was considered to be one with heavy rain. On three days the rainfall was particularly heavy; the mean

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2 The results are discussed in Scientific Report No. 18 of the Institute of Atmospheric Physics of the University of Arizona by L. J. Battan and A. R. Kassander, Jr., 1 March 1962. At the completion of the cloud seeding tests the results will be published.
rainfall exceeded 0.4 inch. These days were regarded as having had very heavy rain. When some rain was measured, but \( \bar{R} \) was less than 0.01 inch, the day was considered to be one with light rain. The average properties of the three sets of days are shown in Table 1. Note that the total amount of rain during 1961 and 1962 was normalized from a 35-gage network to a 29-gage network. Total rainfall quantities are included merely to show the very large differences between the two categories.

Also included in Table 1 are mean values of precipitable water (surface to 400 mb) and the Showalter Stability Index for the morning (0500 MST) and afternoon soundings (1700 MST).

As can be seen from the table and the mean soundings shown in Fig. 2, the differences between precipitable water and stability on days with light and heavy rain were small, but as one would expect, the water vapor content of the atmosphere was higher on days with heavy rain. Thermal instability measured by the Showalter Stability Index was somewhat greater on days with heavy rainfall, but this difference is largely a reflection of higher moisture values in the low levels (specifically at the 850-mb level) of the atmosphere. Thermal instability measured as the temperature difference between the 850-mb and 500-mb levels was smaller on days with heavy rain. This result suggests that the more crucial factor discriminating days with heavy rain from days with light rain was the moisture properties of the atmosphere rather than the temperature structure. Similar suggestions were proposed some time ago by Chalker (1949).

An interesting point to note in the soundings shown in Fig. 2 is that the diurnal change of upper level moisture was different on days with heavy and light rain. In the former category, there was an increase in average mixing ratios above about 800 mb during the time period 0500 to 1700 MST. On the days with light rain, the upper level mixing ratio decreased from morning to afternoon. As can be seen, the temperature curves in both categories were close to the same. At the 500-mb level, the afternoon temperature was about 1C higher than the morning temperature. The same difference is found all the way up to the 100-mb level and is probably caused by radiational heating of the radiosonde.

It might be speculated that the changes of mixing ratio at any particular altitude are caused by net upward or downward motions between the times of observation. Again, considering the 500-mb level, an altitude change of about 600 m could account for the observed mixing ratio changes. Over a 12-hour period, the mean vertical speed to account for 600 m displacement would be about 1 cm sec\(^{-1}\)—up in the case of heavy-rain days, down in the case of light-rain days. These vertical motions would, in the absence of nonadiabatic effects, cause predictable changes in air temperature—an increase on days with descending air and a decrease on days with ascending air. However, as already noted, the temperature curves in the upper levels of the atmosphere were virtually the same on both sets of days. Of course, it may be very unrealistic to assume adiabatic conditions, especially on days with heavy rain. Thus, a satisfactory explanation of the observed discrepancy in the behavior of upper level moisture quantities still cannot be offered.

3. Precipitation and cloud top temperature

As shown by Braham, Reynolds and Harrell (1951) and others, if the fraction of clouds containing a pre-

![Fig. 1. Location of rain gages over Santa Catalina Mountains during the summers of 1957 to 1960.](image-url)
Fig. 2. Mean soundings on days of "light rain" (2a) and days with "heavy rain" (2b).
precipitation echo is plotted against the temperature of
the cloud top, one obtains a curve such as the solid one
in Fig. 3. With very tall clouds, the likelihood of pre-
cipitation is very high. Clouds of very small thickness
almost never rain. As shown by Battan and Braham
(1956) the scale of temperatures (or altitudes) on the
abscissa changes from one geographical region to the
next.

It has been envisioned that when ice nuclei are
introduced into supercooled convective clouds, various
physical processes may take place. It has been proposed
that the precipitation process may be initiated in clouds
which would not precipitate naturally. If this occurred,
it would have the effect of moving a point originally at
N to the point S. It has also been proposed that ice-
nuclei seeding might initiate precipitation earlier in
the life of a cloud than would be the case if it were left
unseeded. If this were to occur, it would have the effect
of moving point N to point S. Thus, the effects of pre-
cipitation initiation in naturally non-raining clouds and
early initiation in rain clouds, would be to shift the
curve in Fig. 3 to the left. A curve such as the dashed
one would be expected as a result of ice-nuclei seeding.

In most cloud seeding programs, it has been assumed
that if the results just discussed could be brought about
there would be measurably more rainfall at the ground.
If this were true, one might expect to find that, in
nature, days with heavy rain are characterized by a
curve such as the dashed one, and light rain days by a
curve such as the solid one. You would certainly expect
such a difference if precipitation initiation were a
crucial factor in determining the quantity of rainfall.
This point was investigated by means of cloud photo-
graphs and radar observations collected during the
years 1957 to 1962.

A pair of ground-located aerial cameras recorded
cloud formations over the Santa Catalina Mountains
on most of the days used to obtain the data listed in
Table 1. Stereographic analysis techniques allowed
measurements of cloud-top heights. Radiosonde data
taken at Tucson were used to obtain cloud-top tem-
peratures. A 3-cm, modified AN/TPS-10 radar set was
employed to observe whether or not each cloud had an
echo at the time of the cloud-top measurements.

The results of the analysis are shown in Fig. 4 for
days with heavy and light rain. The relevant data are
shown at the top of the illustration. It is clear that the
difference between the two curves is quite small. The
results certainly do not resemble the shift in curves
postulated in Fig. 3. If differences between the curves
corresponding to the extremes of precipitation used
here are so small, it certainly is not reasonable to expect
detectable shifts in the curve when rainfall increases
of the order of 20 per cent are sought.

The conclusion from this analysis is that rainfall
differences between days with heavy and light rain
cannot be explained on the basis of the precipitation
initiation mechanism. Furthermore, it leads to the
speculation that any seedling techniques aimed at in-
creasing precipitation by influencing precipitation initia-
tion in convective clouds of the type included in this
analysis, is not likely to have success.

4. Precipitation, cloud size and number

The major difference between days with heavy and
light rain was in the number and size of the clouds.
A measure of these quantities was obtained by means
of the vertically-scanning radar set. At 30-minute

<table>
<thead>
<tr>
<th>Number of days</th>
<th>15</th>
<th>20</th>
<th>25</th>
<th>30</th>
<th>35</th>
<th>40</th>
<th>45</th>
<th>50</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Light rain: total</td>
<td>36</td>
<td>97</td>
<td>85</td>
<td>59</td>
<td>35</td>
<td>12</td>
<td>8</td>
<td>2</td>
<td>-</td>
</tr>
<tr>
<td>Light rain: total</td>
<td>31</td>
<td>219</td>
<td>201</td>
<td>171</td>
<td>131</td>
<td>74</td>
<td>47</td>
<td>11</td>
<td>3</td>
</tr>
<tr>
<td>Ratio: Heavy/Light</td>
<td>1.9</td>
<td>2.0</td>
<td>2.6</td>
<td>3.3</td>
<td>3.8</td>
<td>4.0</td>
<td>4.0</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
clouds remains unfrozen once a cloud extends to temperature levels of \(-5\), \(-10\), or \(-15\)°C still remains unanswered.

Malkus and Simpson (1964) have re-examined the effects of ice nuclei seeding on the release of heat of fusion. On the basis of theoretical considerations and a limited number of seeding experiments they express the view that silver-iodide seeding in large doses can cause certain convective clouds to grow much larger than would be the case if they were left unseeded.

In the tests conducted at the University of Arizona, it was not possible to show that silver-iodide seeding caused a significant increase in the number of large radar echoes. If the effects of “artificially” released latent heat were real, they were too small to be detected by means of our experiments.

5. Precipitation and cloud-to-ground lightning

Visual counts of cloud-to-ground lightning over the Santa Catalina test network were made from a U. S. Forest Service lookout tower located on a mountain peak at 8,500 ft. The differences between heavy- and light-rain days are shown in Table 3.

<table>
<thead>
<tr>
<th></th>
<th>Number of days</th>
<th>Number of lightning strokes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Light rain: total</td>
<td>29</td>
<td>90</td>
</tr>
<tr>
<td>Light rain: per day</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Heavy rain: total</td>
<td>23</td>
<td>4021</td>
</tr>
<tr>
<td>Heavy rain: per day</td>
<td>175</td>
<td></td>
</tr>
</tbody>
</table>

On heavy-rain days there was an average of about 56 times more lightning strokes than on light rain days. If the average rainfall tabulated in Table 1 for each group of days is divided by the average number of strokes per day, it is found that in both rainfall categories the value equals about 0.03 mm of rainfall per stroke. This indicates a correlation between rainfall and cloud-to-ground lightning. Kuettnerser (1950) observed on a mountain top that most active lightning occurred in the region of heaviest precipitation. Still earlier Workman and Holzer (1942) reported that the greatest lightning activity was associated with clouds of greatest vertical extent. Since these clouds also produce the heaviest rainfall, the lightning-precipitation correlation follows directly.

Fig. 5 shows the correlation between precipitation and cloud-to-ground lightning. In this diagram the crosses represent days used in the earlier analysis. The dots represent days with medium quantities of rainfall. The considerable scatter in this diagram is not surprising, particularly on days with lighter rainfall. On such days, showers were widely scattered and short-
lived. Thus, the limited number of rain gages could introduce a substantial variability. Secondly, the visual lightning counts had some built-in subjectivity. The straight line was sketched in to represent what appears to give a reasonable relation. The equation in the upper part of the diagram describes the curve. The consequences of this curve are clear. The greater the rainfall from convective clouds of southeastern Arizona, the greater the number of cloud-to-ground strokes.

As already noted, of the order of 0.03 mm of rainfall was measured for each cloud-to-ground lightning stroke observed. When this average amount of water falls on the network having an area of about 1000 km², the total quantity of precipitation at the ground would be $3 \times 10^{10}$ gm. Braham (1952) and others have shown that evaporation in the downdraft can cause an appreciable reduction in the rainfall. If it is assumed that evaporation caused a 50 per cent reduction in the quantity of falling precipitation, the amount of rainwater in the cloud would be $6 \times 10^{9}$ gm for each lightning stroke. If the charge-separation mechanism is associated with the precipitation mechanism as has been proposed by numerous investigators, this analysis leads to the conclusion that $6 \times 10^{9}$ gm of water (or ice) has to be involved in order to produce sufficient charge for a single lightning discharge.

If a lightning stroke discharged 20 coulombs of charge, charge is produced at a rate of $3.3 \times 10^{10}$ coulombs per gram or 1 esu per gm of precipitation. This is the same order of magnitude which one would infer from the earlier studies (see Mason, 1957).

6. Discussion and summary

On the basis of this study, it is concluded that the microphysical aspects of convective clouds which govern precipitation initiation play a much smaller role in determining the quantity of rainfall from convective clouds than was once suspected. All the new evidence presented was collected in southeastern Arizona but similar conclusions follow from the work in the Middle West of the cloud physics group at the University of Chicago. It seems reasonable to expect that convective clouds forming in moist, tropical air would be governed by the same physical processes regardless of geographical area.

The results indicate that rainfall at the ground and the frequency of cloud-to-ground lightning increase as the number, size, and duration of the convective clouds increase.

The results of this study lead to the conclusion that those properties of the atmosphere which govern the characteristics of the updrafts are the ones which chiefly control the quantity of rainfall and lightning. It follows that it is important to learn more about the relations between the medium- and large-scale properties of the free atmosphere and the characteristics of convective clouds.

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REFERENCES


