# DEVELOPMENT OF PRECIPITATION EFFICIENCY HYPOTHESES FOR SEEDED AND NATURAL CUMULUS CLOUDS USING RESULTS FROM A WEATHER MODIFICATION EXPERIMENT

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## ABSTRACT

A conceptual model based on basic cloud physics reasoning has been combined with the results of a summer cloud seeding program (Project Cloud Catcher) to formulate hypotheses of precipitation efficiency in cumulus clouds. The hypotheses describe the dominant physical characteristics or mechanisms which are responsible for the efficiency with which a cloud system (seeded or unseeded) precipitates.

## INTRODUCTION

Precipitation enhancement can work in three different ways. One way is by increasing the efficiency with which a cloud turns its condensed water into rain. Another is by increasing the amount of water the cloud processes. A third way combines the first two. This paper considers the first of these mechanisms. Using the data from a cumulus cloud seeding experiment, estimates of precipitation efficiency were made for each test cloud system. Then each test case was scrutinized in an attempt to identify dominant physical characteristics or mechanisms which might be responsible for the zero, very low, low,medium or high efficiency with which it precipitated. From this information generalized hypotheses were formulated. The test cases were subdivided according to the best match between their physical characteristics or anticipated precipitation mechanisms and the hypothesis descriptions. Then differences between these groups of test cases were examined for statistical significance.

## THE EXPERIMENT

The Institute of Atmospheric Sciences, South Dakota School of Mines and Technology, conducted a cloud seeding experiment (termed "Project Cloud Catcher") near Rapid City, South Dakota, from approximately June 1 to August 15 of 1969 through 1972. The details of this project are described by Dennis and Koscielski (1972) and Koscielski and Dennis (1972).

Project Cloud Catcher was a randomized field experiment designed to determine the effects of salt and silver iodide[†] seeding upon convective

[†] Will also be referred to as AgI.

clouds in the northern Great Plains. The primary data acquisition sources were radar, instrumented aircraft, time-lapse cloud cameras, and a rain gage network. Test cases were declared on clouds ranging from small, isolated cumuli to groups of towering cumuli already showing radar echoes. Values of $Z_e$, the equivalent radar reflectivity factor, were recorded on magnetic tape. Rainfall for each test case was estimated through the use of $Z_e$-R relationships.

## PRECIPITATION ESTIMATES

Two different radars were used in the project. A 3.2-cm radar was used during the first 2 years, and a 10-cm set was used the last 2 years. Consequently, two different $Z_e$-R formulas were used to transform radar reflectivity to rainfall. Rainfall in the test cases of 1969 and 1970 was estimated by converting the equivalent radar reflectivity factors at 10,000 feet to rainfall rates by the relation $Z_e = 200\ R^{1.6}$. The formula $Z_e = 155\ R^{1.88}$ was used in computing rainfall for the 1971 and 1972 cases. The first relation is the familiar Marshall-Palmer (1948) formula while the second was developed in connection with the North Dakota Pilot Project (Smith, et al., 1975). $Z_e$ is in $mm^6/m^3$ and R is the rainfall rate in mm/hr. The precipitation from each test case was obtained by summing the contributions of precipitation from all cells within the test. In some cases only a fraction of the cells precipitated.

## CONDENSED WATER ESTIMATES

The total water condensed by a convective cell is a function of the vertical flux of air, its water vapor characteristics, the vertical and horizontal areas of influence, the duration of the upward motion, and entrainment of environmental air through the top and sides. Most of these factors vary both spatially and temporally, especially the updraft area, updraft speed, and entrainment. Since Project Cloud Catcher was not designed to obtain detailed space and time measurements of these factors, for this study estimates were made of the average values of those quantities that are directly related to the condensation process. The total water condensed (TWC) by each cell then was estimated according to the following relationship:

$$TWC = A \cdot W \cdot \rho \cdot \Delta MR \cdot t \qquad (1)$$

A is the average area of the updraft, W is the average updraft speed, $\rho$ is the air density, $\Delta MR$ is the mixing ratio difference between base and top of the cell and t is the duration of the updraft, Entrainment was neglected.

For this investigation the following procedure was used in estimating the total water condensed for each test case:

(1) Condensed water was estimated for each cell within the test cases.

a. The updraft area (A) and duration of cell life (t) were estimated from radar data and time-lapse cloud photographs.

b. The updraft speed (W) was obtained utilizing the output from a one-dimensional, steady-state convective cloud model (Hirsch, 1972). This model was run on a representative sounding for each experimental day. It predicts different cloud depths depending on the updraft radius that is assumed. The model-generated cloud depth chosen as the one representative of each case generally was the one closest to the actual cell having the largest depth. The maximum updraft speed in the model-computed updraft profile was the one used in the computation of condensed water.†

c. The air density ($\rho$) was computed for cloud base height using radiosonde information.

d. The mixing ratio difference ($\Delta MR$) was computed from a thermodynamic chart considering average cloud base and top characteristics.

(2) The total condensed water was a summation of the condensed water for all cells in that case.

## SAMPLE SIZE

Table 1 summarizes sample size characteristics of the cloud Catcher data. Of the 122 cases that were analyzed, nearly twice as many were obtained during the first 2 years compared with the last 2 years and there were significantly more single-cell cases during the first 2 years. Forty percent of the cases fell in this category while less than 10 percent were so characterized during the last 2 years.

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† Based on model results as of May, 1974.

Table 1

Number of Cloud Catcher cases analyzed and the number of individual cells involved. (Percentage of total is shown in parenthesis)

| | 1969-70 | 1971-72 | 1969-72 |
|---|---|---|---|
| Number of cases | 80 | 42 | 122 |
| Natural | 33 (41%) | 13 (31%) | 46 (38%) |
| Salt seed | 29 (36%) | 21 (50%) | 50 (41%) |
| Silver iodide | 18 (23%) | 8 (19%) | 26 (21%) |
| Number of cells | 170 | 117 | 287 |
| Cases with one cell | 32 (40%) | 4 (9%) | 36 (30%) |
| Cases with two cells | 23 (29%) | 15 (36%) | 38 (31%) |
| Cases with three cells | 13 (16%) | 13 (31%) | 26 (21%) |
| Cases with four or more cells | 12 (15%) | 10 (24%) | 22 (18%) |

## CONCEPTUAL MODEL OF PRECIPITATION EFFICIENCY

General hypotheses of how the precipitation process operates in both natural and seeded clouds have been presented in references ranging from meteorology and cloud physics text books to cloud seeding experiment reports. The objective of this section is to combine general hypotheses based on basic cloud physics reasoning with experimental results to arrive at more specific hypotheses regarding precipitation efficiency expectations from various type cloud systems. The hypotheses have been divided among five categories of expected efficiencies - zero, very low, low, medium, and high. Each hypothesis is stated (1) in a general form and then (2) in specific terms as the Cloud Catcher data seemed to support it.

## ZERO EFFICIENCY

### Hypothesis #1

1) Shallow clouds are too short lived, have updrafts too slow and liquid-water-contents too low to produce any precipitation by the all-water condensation -coalescence process.

2) Any clouds less than 2 km deep or less than 4 km deep when cloud base temperatures are warmer than 2°C (whether seeded or not) are not expected to produce precipitation.

VERY LOW EFFICIENCY

Hypothesis #2

1) Deep clouds whose tops reach to the -40°C† level or higher and which have strong updrafts create extensive cirrus shields and precipitate inefficiently. These cloud systems can be made even more inefficient through ice phase seeding which freezes up more of the cloud water that would normally be used in accretional growth of precipitation particles.

2) Clouds whose tops are colder than -40°C and are seeded with AgI are expected to be very inefficient precipitators.

Hypothesis #3

1) Medium depth clouds are long lived enough, have moderate updrafts and high enough liquid-water-contents to produce efficient precipitation primarily by an all-water coalescence and drop breakup process. Ice phase seeding can significantly reduce the precipitation efficiency by freezing up the drop multiplication and growth regions.

2) Clouds whose depths range about 5 to 6 km and whose tops are warmer than -30°C are expected to precipitate very inefficiently when seeded with AgI.

Hypothesis #4

1) Shallow-to-medium depth clouds, while potentially deep enough to support an effective coalescence process, often are so narrow that entrainment shortens their lifetimes and shrinks the areas of high liquid-water-content thereby reducing their rain production significantly.

2) Clouds whose depths range about 4 to 5 km and whose widest cell has a diameter less than about 1 km (whether seeded or not) are expected to precipitate very inefficiently.

Hypothesis #5

1) Deep clouds with excessively strong updrafts are inefficient because most of the precipitation embryos do not have time to grow to adequately sized rain or graupel particles. Such systems produce extensive cirrus clouds but little rain.

2) Unseeded clouds whose top temperatures are colder than -30°C, which have a maximum updraft speed greater than 25 m/sec (as predicted by the Hirsch convective model) and are predicted not to allow sufficient

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† Cloud top temperatures were estimated using a thermodynamic chart and assuming a moist-adiabatic ascent from cloud base to top.

time for precipitation formation by a single particle microphysics model,† are expected to precipitate very inefficiently. AgI seeding probably would have little or no positive effect on the precipitation formation mechanism.

## LOW EFFICIENCY

### Hypothesis #6

1) Deep clouds with strong updrafts are inefficient because precipitation forms high up where cloud is mostly ice. These systems also produce extensive cirrus clouds.

2) Unseeded clouds whose top temperatures are colder than -30°C, which have maximum updraft speeds within the range 15 to 25 mm/sec (as predicted by the Hirsch convective model) and are predicted to have sufficient time for precipitation formation by a single particle microphysics model, are expected to precipitate inefficiently, although somewhat better than the stronger updraft cases described in Hypothesis #5.

## MEDIUM EFFICIENCY

### Hypothesis #7

1) Medium depth clouds are long lived enough, have moderate updrafts and high enough liquid-water-contents to produce efficient precipitation primarily by an all-water coalescence and drop breakup process. Hygroscopic seeding can reduce the precipitation efficiency somewhat because the seeding embryos do not travel as high up into the cloud as the natural embryos would have, therefore they don't sweep out as much water and consequently are smaller when precipitating out the cloud base. It might also decrease the effectiveness of the drop breakup zone.

2) Salt seeded clouds whose depths range about 5 to 6 km and whose tops are warmer than -30°C are expected to precipitate somewhat less efficiently than if they had been left unseeded.

### Hypothesis #8

1) Shallow-to-medium depth clouds, while potentially deep enough to support an effective coalescence process, often are so narrow that entrainment shortens their lifetimes and shrinks the areas of high liquid-

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† A one-dimensional, steady-state, microphysics model developed by Musil (1970), which computes the growth of a precipitation particle in a specified cloud environment was used to objectively estimate whether precipitation could form before embryos exit through cloud top.

water-content thereby reducing their rain production significantly. When the clouds are wide enough to diminish the effects of entrainment, this potential can be realized.

2) Clouds whose depths range about 4 to 5 km and whose widest cell has a diameter greater than about 1.5 km (whether seeded or not) are expected to precipitate fairly efficiently, although not as efficiently as the slightly deeper clouds.

Hypothesis #9

1) Deep clouds with strong updrafts are inefficient because precipitation forms high up where the cloud is mostly ice. These systems produce extensive cirrus clouds. They can be made more efficient through hygroscopic seeding which speeds up the precipitation formation mechanism.

2) Salt seeded clouds whose top temperatures are colder than -30°C and which have a maximum updraft speed within the range 15 to 25 m/sec (as predicted by the Hirsch convective model) are expected to precipitate somewhat more efficiently than if they had been left unseeded.

The quantity of salt used in the experiment probably was much less than optimum for this size cloud, and efficiencies may have been higher if optimum quantity was used.

## HIGH EFFICIENCY

Hypothesis #10

1) Medium-to-deep clouds cannot attain maximum efficiency by an all-water coalescence process and are not cold enough to maximize the benefits of a diffusion and low density accretion ice growth (Bergeron) process. The efficiency of these systems can be increased through ice phase seeding.

2) AgI seeded clouds whose top temperatures are between -30°C and -40°C precipitate very efficiently.

Hypothesis #11

1) Shallow clouds which are too short lived, have updrafts too slow and liquid-water-contents too low to produce any precipitation by the all-water condensation-coalescence process can be efficient precipitators when the Bergeron process can operate.

2) Clouds whose depths range 2 to 4 km, whose top temperatures range about -4°C to -22°C and which are either seeded with AgI or have cloud base temperatures colder than 3°C precipitate very efficiently.

Hypothesis #12

1) Medium depth clouds are long lived enough, have moderate updrafts and high enough liquid-water-contents to produce efficient precipitation primarily by an all-water coalescence and drop breakup process.

2) Unseeded clouds whose depths range about 5 to 6 km and whose tops are warmer than -30°C are expected to precipitate very efficiently.

Hypothesis #13

1) Deep clouds with moderate updrafts are very efficient because precipitation forms lower in the cloud and diffusion and accretion growth of the precipitation particles uses up much of the cloud water that would be processed out the top as cirrus if the updrafts were stronger.

2) Salt seeded and unseeded clouds whose top temperatures are colder than -30°C and have a maximum updraft speed less than 15 m/sec (as predicted by the Hirsch convective model) are expected to precipitate very efficiently.

## DISCUSSION

A condensed summary of the hypotheses just discussed appears as part of Table 2. This table lists the estimated precipitation efficiencies and amounts for the Cloud Catcher cases (ranked on efficiency) that fall under each hypothesis. Some of the hypotheses have only a few cases supporting them. Five out of the thirteen hypotheses have fewer than six cases supporting them, and three have fewer than four cases. Five of the hypotheses have fairly good support (from a statistical testing viewpoint), with more than ten cases under them.

Definite overestimates (>1.0) of precipitation efficiency were made for eighteen cases. The maximum possible efficiency value of 1.0 has been assigned in these situations.

An analysis of the distribution of efficiencies that have been placed in each category according to the conceptual model shows that the data lend support to the various hypotheses. Figure 1 is a relative frequency histogram of the estimated precipitation efficiencies for the Cloud Catcher cases in each expected efficiency category. Both the sequence of median efficiencies and the graphical representation show a shift toward higher efficiencies as one progresses from the zero to high efficiency categories.

A Rank-Sum test was applied to various combinations of population samples (of efficiencies) in order to determine whether or not their differences were significant. The combinations chosen basically shared the same cloud depth characteristics. For instance the sample form Hypothesis #7 was compared with #12. Both were for medium depth clouds, salt seeded in Hypothesis #7 and left unseeded in Hypothesis #12. The results of these tests are summarized in Table 3. Of the sixteen tests performed only two

Table 2

Estimated precipitation efficiencies and amounts from Cloud Catcher cases which meet the hypothesis requirements (ranked on efficiency).
Table lists precipitation efficiency, precipitation amount (KTONS), then seeding indicator N, S, or A which signifies no seed, salt seed, or silver-iodide seed, respectively.

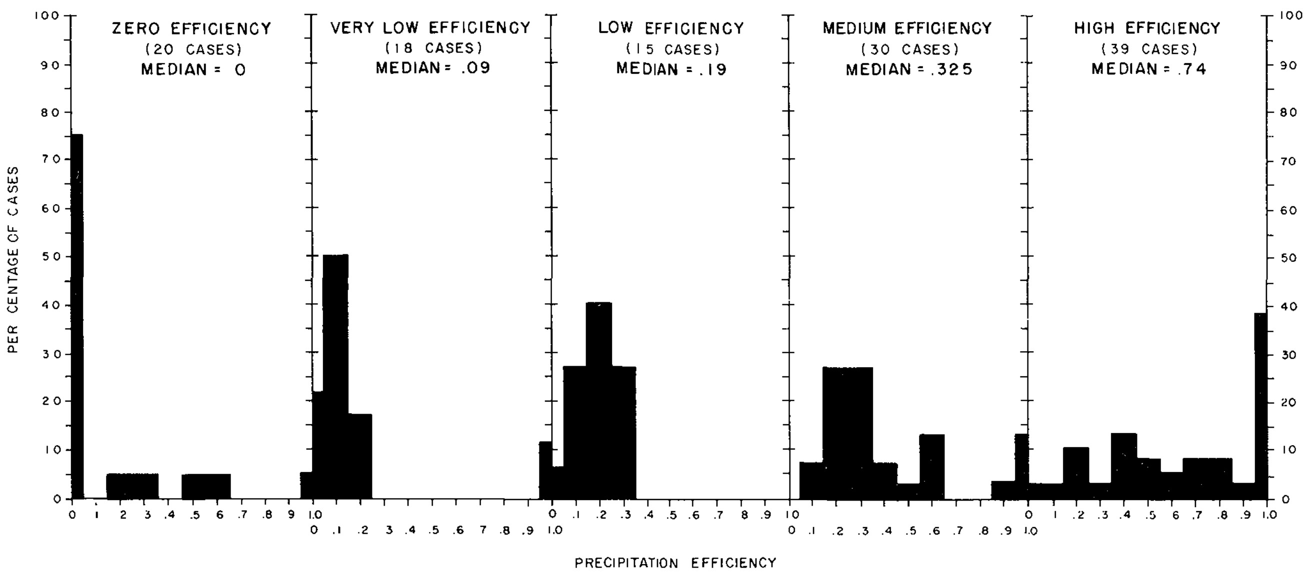
| ZERO EFFICIENCY | VERY LOW EFFICIENCY | | | | LOW EFFICIENCY | MEDIUM EFFICIENCY | | | HIGH EFFICIENCY | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Hypothesis #1 | Hypothesis #2 | Hypothesis #3 | Hypothesis #4 | Hypothesis #5 | Hypothesis #6 | Hypothesis #7 | Hypothesis #8 | ** Hypothesis #9 | Hypothesis #10 | Hypothesis #11 | Hypothesis #12 | Hypothesis #13 |
| 0 0 N | .08 3690 A | 0 0 A | 0 0 N | .09 197 N | .04 319 N | .11 62 S | .38 394 N | .11 26 S | .32 603 A | 0 0 A | .60 464 N | .15 128 N |
| 0 0 N | .09 1476 A | .05 5 A | .04 6 N | .14 1230 N | .06 444 N | .31 331 S | 1.0* 218 A | .17 5542 S | .38 680 A | .22 12 A | .74 36 N | .18 615 S |
| 0 0 N | .11 462 A | .08 62 A | .07 4 N | .22 614 N | .08 648 N | .32 369 S | | .19 1603 S | .61 1154 A | .23 2 A | .79 253 N | .21 17 S |
| 0 0 N | | .12 42 A | .07 6 N | | .12 2897 N | .33 701 S | | .20 674 S | .71 109 A | .45 476 A | 1.0* 47 N | .41 1042 S |
| 0 0 N | | .20 62 A | .16 4 N | | .14 1011 N | .37 62 S | | .20 931 S | .78 143 A | .51 11 A | 1.0* 279 N | .43 1036 S |
| 0 0 S | | | 1.0* 141 N | | .17 151 N | .58 143 S | | .21 2310 S | 1.0* 64 A | .98 64 A | | .44 144 N |
| 0 0 S | | | 1.0* 53 S | | .17 1676 N | 1.0* 246 S | | .22 246 S | | 1.0* 143 A | | .47 123 N |
| 0 0 S | | | | | .19 825 N | | | .23 460 S | | 1.0* 17 S | | .48 2972 S |
| 0 0 S | | | | | .22 1011 N | | | .25 2438 S | | 1.0* 18 S | | .67 519 N |
| 0 0 S | | | | | .23 1305 N | | | .27 1476 S | | 1.0* 33 A | | .78 1230 S |
| 0 0 S | | | | | .25 765 N | | | .28 93 S | | 1.0* 191 S | | .92 542 S |
| 0 0 S | | | | | .26 1064 N | | | .31 1214 S | | 1.0* 62 A | | 1.0 1148 N |
| 0 0 A | | | | | .28 1070 N | | | .34 617 S | | | | 1.0* 1446 N |
| 0 0 A | | | | | .30 1176 N | | | .35 1189 S | | | | 1.0* 74 S |
| .01 2 N | | | | | .33 1036 N | | | .53 572 S | | | | 1.0* 36 S |
| .18 20 N | | | | | | | | .58 1182 S | | | | 1.0* 95 N |
| .31 6 S | | | | | | | | .59 604 S | | | | |
| .48 2 S | | | | | | | | .60 288 S | | | | |
| .57 8 N | | | | | | | | .87 159 S | | | | |
| 1.0* 6 N | | | | | | | | 1.0* 1134 S | | | | |
| | | | | | | | | 1.0* 1764 S | | | | |

DESCRIPTION OF HYPOTHESES (See text for more detailed discussion.)

1. Zero Efficiency - Shallow clouds, all clouds less than 2 km deep or less than 4 km deep when cloud base temperatures warmer than 2° C (whether seeded or not). Too short lived for effective coalescence process.
2. Very Low Efficiency - Deep clouds, top temperatures colder than -40° C (AgI seed). Seeding decreases accretion efficiency by freezing more of cloud water.
3. Very Low Efficiency - Medium depth clouds (AgI seed). Seeding interferes with efficient all-water coalescence process.
4. Very Low Efficiency - Shallow-to-medium depth clouds, about 4 to 5 km deep, diameter of widest cell less than about 1 km (whether seeded or not). Entrainment decreases efficiency.
5. Very Low Efficiency - Deep clouds, Hirsch model maximum updraft speed greater than 25 m/sec (no seed). Most of cloud water goes into creation of cirrus anvil.
6. Low Efficiency - Deep clouds, Hirsch model maximum updraft speed 15 to 25 m/sec (no seed). Precipitation forms high up where cloud is mostly ice.
7. Medium Efficiency - Medium depth clouds (salt seed). Salt seeds do not sweep out as much water as natural embryos.
8. Medium Efficiency - Shallow-to-medium depth clouds, about 4 to 5 km deep, diameter of widest cell greater than about 1.5 km (whether seeded or not). Effects of entrainment greatly diminished.
9. Medium Efficiency - Deep clouds, Hirsch model maximum updraft speed 15 to 25 m/sec (salt seed). Seeding speeds up precipitation formation mechanism.
10. High Efficiency - Medium-to-deep clouds, about 5 to 7 km deep with top temperatures -30° C to -40° C (AgI seed). Seeding maximizes benefits of Bergeron process.
11. High Efficiency - Shallow clouds, 2 to 4 km deep with top temperatures -4° C to -22° C (AgI seed or base temperature colder than 3° C). Bergeron process effective here.
12. High Efficiency - Medium depth clouds (no seed). All-water coalescence process and drop breakup produces highly efficient precipitators.
13. High Efficiency - Deep clouds, Hirsch model maximum updraft speed less than 15 m/sec (salt and no seed). Coalescence and Bergeron processes optimized due to slower updrafts.

Shallow: Clouds generally 1.5 to 4 km deep, top temperature warmer than -25° C.
Medium : Clouds generally 5 to 6 km deep, top temperatures warmer than -30° C.
Deep : Clouds generally deeper than 6 km, top temperatures colder than -30° C.

*Efficiency calculated to be greater than unity and set to its maximum possible value (1.0).
**Sufficient dose (quantity) of hygroscopic material probably was not used in these cases.




produced probabilities greater than .10 (the lower the probability level, the more significant is the difference between the samples). Seven tests resulted in probability levels of less than or equal to .005 while twelve had probabilities of .025 or lower. As encouraging as these results may appear, they must still be interpreted with restrained enthusiasm, particularly in the situations where one of the samples involved has only a few elements in it. However, four of the test results seem to lend solid support toward the credibility of certain of the conceptually conceived hypotheses. The four test comparisons were Hypotheses #1 vs #11, #6 vs #9, #6 vs #13, and #9 vs #13. Each sample in these combinations had at least twelve elements.

Table 3

Probability levels from Rank-Sum test which tests the null hypothesis that the medians (of efficiencies) of two populations are equal against a one-sided alternative. See text or Table 2 for description of hypotheses.

(Number of cases under each hypothesis is shown in parenthesis)

| Hypothesis Number | 6 (15) | 7 (7) | 8 (2) | 9 (21) | 10 (6) | 11 (12) | 12 (5) | 13 (16) |
|---|---|---|---|---|---|---|---|---|
| 1 (20) | | | | | | .005 | | |
| 2 (3) | .10 | | | .005 | | | | .005 |
| 3 (5) | | .025 | | | .005 | | .005 | |
| 4 (7) | | | >.10 | | | | | |
| 5 (3) | >.10 | | | .025 | | | | .025 |
| 6 (15) | | | | .005 | | | | .005 |
| 7 (7) | | | | | .10 | | .025 | |
| 9 (21) | | | | | | | | .025 |

## CONCLUDING REMARKS

The hypotheses that have resulted from this study support the view that considers precipitation mechanisms within convective clouds as being affected by many cloud processes. They further suggest that an order of domination of physical mechanisms which affect precipitation efficiency exists, and that a single higher ordered mechanism can drastically shift the efficiency up or down.

In order to gain acceptance, the conceptual model hypotheses need to be tested on other data to see if they provide similar support. The hypotheses should also be tested on numerical cloud models. The controlled environment of these models probably provides the best opportunity not only for recognizing whether these theories are true but also for defining their limits of effectiveness.

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